OPTIMAL POWER DISPATCH IN DEREGULATED MARKET CONSIDERING CONGESTION MANAGEMENT

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February, 2000

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A Thesis Submitted
in Partial Fulfillment of the Requirements
for the Degree of

MASTER OF TECHNOLOGY

By

PERVEEN KUMAR

to

DEPARTMENT OF ELECTRICAL ENGINEERING

INDIAN INSTITUTE OF TECHNOLOGY, KANPUR

FEBRUARY, 2000

dedicated

to

my Parents

Certificate

It is certified that the work contained in the thesis entitled **OPTIMAL POWER DISPATCH IN DEREGULATED MARKET CONSIDERING CONGESTION MANAGEMENT** by *Perveen Kumar* has been carried out under my supervision and this work has not been submitted elsewhere for a degree.

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25 February, 2000

Abstract

The electric utility industry is undergoing rapid changes due to restructuring and deregulation. The significant feature of these changes is to allow for competition among generators of electricity, to offer a low price, higher quality and more secured product. The changing nature of the electricity utility industry has brought many new practices to power system operation. The deregulation of electricity market has been accompanied by variety of problems. Under a competitive environment, generation is not centrally dispatched, but, rather, it is based primarily on the transactions agreed to in the open market. In the market situation, the difficulty lies in ensuring the negotiated transactions, particularly under congestion. In a competitive power market, the task of an independent system operator (ISO) is to ensure full dispatch of the contracted power. However, if it causes the line flows exceeding their limits, thus threatening the system security, the ISO makes decision on the curtailment of the contracted power. An optimal power dispatch (OPD) model has been presented in this work to minimize the curtailment of the contracted powers in a power market having bilateral, multilateral as well as firm contracts. A strategy has been suggested for allocation of transmission losses among various market participants. Role of flexible AC transmission system (FACTS) devices on reducing the transmission congestion and curtailment of the contracted power has also been studied. Study has been conducted on modified IEEE-14 bus system and UPSEB-75 bus system. The proposed OPD results show that higher premium price of willingness to pay by a group lower the curtailment in the desired transaction of that particular group. The suitable placement of FACTS devices is helpful in reduction of transmission congestion. Loss allocation strategy suggested in the present work is quite simple and non-iterative.

Acknowledgement

On the completion of the work, I feel it as my greatest privilege to work under the noble and esteemed guidance of Dr. S. C. Srivastava. I can not forget him for excellent supervision, skilled guidance, unfailing support and constant encouragement not only during my thesis work but also during my whole stay at I I T Kanpur. I find no suitable words to express my feelings towards Dr. S. C. Srivastava for his deep concern he has shown for my academics and for my personal life.

I am very much thankful to Professors S. Sachchidanand, S. S. Prabhu and S. Gupta who taught us various courses needed for this work.

I am grateful to my parent department i.e. Military Engineering Services, Ministry of Defence, Govt. of India for sponsoring me to do M. Tech. at I I T Kanpur.

I am especially thankful to Dr. S. N. Singh for providing me the assistance whenever I needed for my thesis through e-mail that helped me a lot.

My family and myself will always remember the affection and attention received from Dr. S. C. Srivastava and his family during our stay at I I T Kanpur.

At lasts but not the least, I express indebtedness to my family members for their unending support, love and affection received from my wife Neelam, son Arpit and daughter Akriti.

Perveen Kumar

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Chapter 1

Introduction

1.1 General

Recently, some of the industries such as telecommunication, airline and gas have experienced major changes resulting from reduced regulation and increased competition. Electric power industry is also undergoing rapid changes that are reshaping an industry that for a long time has been stable and operated as monopolistic market. The significant feature of these changes is to create market condition in the industry, which are seen as necessary to increase the efficiency of electric energy production and distribution, and to offer a lower price, higher quality and more secure product.

Deregulation is essentially re-structuring of the rules and economic incentives that government set up to drive the electric power industry. The driving force behind deregulation movement vary from country to country, coming from many sources that range from political reform, regulatory failures, high tariffs, management inadequacy, global economic crisis, the rise of environmental pollution, the lack of public resources for investment and so on.

The changing nature of the electric utility has brought many new practices to power system operation. Different restructuring models, in which the responsibilities and scope of activities of the system operators vary widely, have been proposed and implemented in different countries.

An open competitive market requires that access to the transmission system by generators and loads are managed in a non-discriminatory manner. In deregulated market, there may be large number of different buyers and sellers combinations. Whenever electricity is traded, the transmission and distribution losses occur. To keep the balance in the system, additional production is, of course, needed to meet the losses. The two basic characteristics of electric power network have to be properly handled to achieve transmission open access viz. transmission congestion and transmission losses. The transmission congestion is to be handled by a third party who is neither buyer nor seller of the electric energy. To co-ordinate among the independent trades and to operate the system in a secure state, a deregulated system plans for an independent system operator (ISO) that monitors and operates the interconnected power system. One important aspect is that ISO runs but does not own the power system. ISO also maintains power flow balance throughout the network and includes the transmission losses in the power balance.

In a regulated power market, the scheduling of generation is done following a centralized unit commitment and economic dispatch algorithm that also ensures that all transmission limits are satisfied. Under a competitive environment, generation is not centrally dispatched but, rather, it is based primarily on the transactions agreed to in the open market. Transmission congestion may occur due to heavy loading, caused by natural market settlements. In the market situation, the difficulty lies in the negotiated transactions and to operate the transmission system in a secure state. Some times transmission congestion can be relieved by technical means, such as operation of flexible AC transmission system (FACTS) devices etc. In a deregulated market, the allocation of total power loss to individual trade is nontrivial. Due to nonlinear nature of the loss relationship, it is difficult to allocate the losses accurately to individual transactions. In general, under congested conditions, transaction levels are non-linearly coupled so that it is difficult to modify one without affecting the others. Congestion will inevitably result in changes in desired market settlements. Thus, gives rise to a debate on how to manage congestion.

1.2 State of art

Recent moves to deregulate power industries to foster generation competition and customer choice have touched off a debate on the following power system operation aspects:

- How the transmission system should be restructured?
- How the transmission pricing should be made in the open access?
- How the contracts shall be made between generating companies and customers?
- How the curtailment on the power transaction should be applied by the ISO in case of the transmission congestion?
- How the transmission losses shall be allocated to the market participants?
- How well the compensatory devices will play an important role in the competitive environment etc.?

Bart et al. [1] had presented a method for the power and energy management, according to minimal costs criteria over one year of an electricity utility, which has to deal with nuclear and hydro power plants considering fixed contracts, variable contracts and exchange contracts. Berrizzi et al. [2] had suggested a model based on security constrained optimal power dispatch considering firm contracts and interruptible contracts that maximizes the real power exchange amongst the different agents of the electricity market. This work has limitations that only bilateral, firm and interruptible contracts can be scheduled. Conejo et al. [3] presented a framework to carryout a multi-area optimal power dispatch in a coordinated decentralized fashion. The framework includes DC non-linear optimal power dispatch model and an algorithm based on the Langrangian relaxation decomposition procedure. The losses were incorporated through additional loads based on cosine approximations. David et al. [4,25,3] modeled power transactions in deregulated market under open transmission access as pool dispatch and bilateral dispatch. A transaction namely ancillary services transaction has been introduced for providing essential ancillary services including transmission loss compensation. A typical five-bus system was considered for illustrating the transaction curtailment strategy under transmission congestion. The objective of the ISO is considered as to maximize the generation cost minus delivery prices. A component called as 'willingness to pay' in case of

congestion to avoid curtailment was also included. This paper, however, has not addressed to the loss allocation strategy among the market participants. Zobian and Marrija Illic [5] had introduced the concept of distributed slack bus to compute the contributions of each transaction to the network power flows through out the interconnected power system in steady state operation. The concept of distributed slack bus was introduced to account for the fact that many generators are participating in economic power dispatch. Formulation was done with the assumption that shunt impedance of the lines can be neglected. However, this may not be practical and may lead to serious computational errors. Yu and David [6] gave the security related long run marginal cost. Analysis of transmission services, the security related marginal wheeling costs of transporting power between buses were carried out using the sensitivities of the MW-mile of each area with respect to bus power demand. The allocation of total power loss to individual trade is non-trivial due to non-linear nature of the loss relationship. Linear approximation of the losses had been used in [11], which always provided over estimate. The method is iterative in nature and requires more computational time. Fang and David [32] proposed a new scheme of rescheduling transactions under congestion of the transmission system. The new set of transactions was the closest point near the desired transactions within the security region. A minimum distance algorithm was presented by Galiana et al. [12, 22, 26] as a means to allocate limited transmission capacity under congested conditions to a set of transactions proposed by the market forces. This algorithm was used to reschedule proposed transactions as well as to trade reserved transaction rights and to allocate transmission losses. Marija Illic et al. [26] had suggested a transmission loss allocation strategy for bilateral transactions. Transmission congestion cost had been dealt by Harry Singh et al. [15], based on nodal pricing framework. Fang and David [32] in their work were confined to only bilateral and multilateral contracts and the reactive power limits of the generators were not considered. The case studies were conducted on modified IEEE-14 bus system. Further in ref. [32] the voltage and angle had been taken as state variables.

Recently, FACTS devices applications [16] have been considered in power system to maximize the use of the existing transmission facilities and to enhance stability limit. Enrique Acha et al. [8] had presented models of some of the FACTS devices namely, Thyristor Controlled Series Compensator (TCSC), Unified Power Flow Controller

(UPFC) and Thyristor Controlled Phase Angle Regulator (TCPAR). Behavior of these devices had been studied with an objective of active power cost minimization and transmission loss minimization using Newton's method. Handschin and Lehmkoster [9] solved a coupled problem of active and reactive power optimization including the FACTS devices. Preecha and Srivastava [30] had presented a static model of TCSC, SVC and TCPAR and had utilized it in the loss minimization studies.

1.3 Motivation

Many developing countries are adopting deregulation in their electricity market. When the deregulation of the power system is introduced, the usage of the existing available generation capacity to its maximum extent and operation of the power system in secure state becomes the prime objective. It is also important to allocate the system transmission losses to the market participants that are due to them. In a deregulated market, the capacity enhancement of the existing transmission facilities through controllable devices may help in the utilization of the generation capacity to its maximum limit. Hence, the motivation behind the present work have been:

- To evolve a systematic and simple approach of rescheduling the transactions under congestion. The suggested method expresses the line flows as a function of the contracted power using linear sensitivity factors and the optimization problem is formulated considering the contracted transactions as the state variables.

- To consider the presence of firm contract, apart from the bilateral and multilateral contracts. For this purpose one of the transactions has been considered to be firm and is not curtailed till the curtailment in other transactions are not sufficient to relieve the congestion in the system.

- To evolve a simple and non-iterative technique of the loss allocation to the market participants having bilateral and multilateral transactions.

- To study the usage of FACTS devices on enhancing the transactions and minimizing the line congestion.

- To extend the study to a practical Indian system The same has been done on UPSEB-75 bus system.

1.4 Thesis Organization

The thesis has been organized in four chapters as described below.
Chapter 1 introduces various aspects and problems associated with deregulation of electric power industry and role of optimal power dispatch in management of transactions, presents a brief state of the art and sets the motivation behind this work reported in the thesis.

Chapter 2 presents a new model of optimal power dispatch (OPD) in deregulated market describing the various curtailment strategies to handle the transmission congestion. Sequential quadratic programming method has been used for the OPD solution. The line flows have been expressed as a function of the contracted power using linear sensitivity factors.

Chapter 3 presents a new non-iterative method of loss allocation amongst players in the various bilateral and multilateral contracts. Impact of some of the FACTS devices, namely Thyristor Controlled Series Compensator (TCSC) and Static VAR Compensator (SVC), in enhancing the transaction is also studied.

Chapter 4 concludes the main findings of the thesis and lists a few suggestions for future scope of work.

Chapter 2

Optimal Power Dispatch Considering Congestion Management

2.1 Introduction

The deregulation of the power system industry has brought distinct changes in the electricity market. From the earlier task of mere distribution of electric energy in a monopolistic situation, in a deregulated electricity market, different agents sell different contracts, offer various commodities and services at different market places.

Under a deregulated environment, generation is not centrally dispatched. The lack of coordination among the independent trades can lead to a violation of transmission network constraints. The network constraints arise from the loading limits on transmission lines and equipments and from the requirement that the network be operated in a secure state. In the competitive electricity market, the generation is based primarily on the transactions agreed to by the market participants. The power system security is very important, since the trade requires a functioning power system. In order to guarantee a free market, the use of ancillary services can not be allowed to interfere with the trade. Therefore, an independent identity called as independent system operator (ISO), controls the power system. To make sure that the ISO does not interfere with the market and stay neutral, the ISO is forbidden to participate in the electricity energy market, but ensures the open access to the transmission system by generators and loads in a non-discriminatory manner. In a competitive power market, the task of an ISO is to ensure full dispatch of the contracted power. However, if it causes the line flows exceeding their limits, thus threatening the system security, the ISO makes decision on the curtailment of the contracted power. In deregulated market

condition, the difficulty lies in ensuring the negotiated power transactions particularly under congested conditions. Congestion will inevitably result in changes in desired market settlements. This gives rise to a debate on how to manage congestion without removing any incentive to compete for capacity in the transmission grid. In general, under congested conditions, transaction levels are nonlinearly coupled so that it is difficult to modify one without affecting the others. There may be a firm power contract with fixed power level during a defined time period, whose curtailment strategy should be different than the other normal contracts.

In most of the research work, optimal operation of power system in deregulated network market has been simulated based on economic criterion [4, 25 and 33]. In [32] a new schematic approach of rescheduling transactions under congestion is proposed. The new set of transactions is the closest point near the desired transactions within the security region. However, in this work, the generator reactive power limits were not considered and the variables were voltage magnitude and angles. Further they did not suggest any strategy for real power loss allocation. In this chapter, the basic optimal power dispatch model described in [32] has been considered but extended on the following aspects.

- The line flows have been considered as linear function of the contracted powers using generalized generation distribution factors as given in [20]. The optimal power dispatch has been solved using a sequential quadratic programming method taking the market transactions as the variables, instead of complex voltages.

- The reactive power limit of the generators has also been considered in the model.

- The presence of multilateral, bilateral and firm contracts have been considered.

The studies have been conducted on a modified IEEE-14 bus system and a practical Indian, Uttar Pradesh State Electricity Board (UPSEB) 75-bus system, which have been slightly modified to represent a deregulated, market situation.

2.2 Proposed Framework for Deregulated Market

A variety of restructuring frameworks has been developed in different countries. In practice, appropriate regulation is essential to protect the public interests and to help in creating a competitive environment for different market participants. There are several ways that a government can decide to adopt deregulated operation of the system.

The initial focus of competition in the electric energy industry was generation. However, it soon became clear that a main hindrance to increasing competition in electric systems was access to the transmission system. Electricity utility companies owned the transmission system, and the non-utility needed transmission access to be competitive. The transmission system is the area where important economics of scale are present, therefore, must continue to be regulated. It is recognized that transmission open access is an essential step to promote efficient competition.

The completely unbundled electric power market will consist of generation companies (GENCOS), distribution companies (DISCOS), energy brokers as well as independent system operator (ISO). All GENCOS and DISCOS will have equal right to access the transmission network. GENCOS will compete in a free market to sell electricity and DISCOS will attempt to choose the cheapest sellers. Assuming that a real-time information network is established, all buyers and sellers can access the same information as the ISO to make their own economic decisions. Furthermore, energy brokers may also enter the competitive environment.

The ISO, as transmission service provider, still controls the whole transmission network but will be independent of market participants. The settlement of the energy markets will be respected by the ISO without discrimination. Its major duty will be confined to having responsibility for system operation and guaranteeing system security. If contracted transactions between market participants can be transmitted without security problems, all transactions will be dispatched by the ISO without curtailment. Otherwise, the ISO will intervene to curtail the requested transactions until the system is within security limits.

It is clear that, in the new situation, economic and security functionalities are separated. Transactions are the financial agreements, when actually implemented, define physical quantities in the network such as load reserves, and generation levels, consequently influencing real power flows, voltage levels, losses, operational costs and system reliability. Transactions must, therefore, be systematically modeled, planned and controlled. Under competition and open transmission access, following four major types of transactions are examined in this thesis viz.

1. *Bilateral transactions:* A bilateral transaction is made directly between a GENCO and a DISCO without third party intervention. Even under the traditional structure, where all generation belong to one entity and all loads buy their power from that entity, it can be agreed that the transaction is bilateral, namely from the individual generators to the individual loads.

2. *Multilateral transactions:* A multilateral transaction is a trade that involves more than two parties and thus is an extension of the bilateral transactions. In some situations, in order to reduce risk in business, GENCOS and DISCOS prefer to make contracts through brokers rather than directly finding the buyers or sellers themselves.

3. *Firm transactions:* A firm power transaction is a trade with fixed power level during a definite time period. It can be either bilateral or multilateral. It is basically done for essential loads. Curtailment to these loads even under the congested condition is done only under the extreme exigencies, when the curtailment to other transactions is not able to relieve the congestion.

4. *System regulation transactions:* System regulation is needed to compensate for transmission losses, to deal with reactive power supply issue, to provide emergency power supplies and black-start capabilities etc. System regulation transactions are a small percentage of all transactions and their cost must be allocated among all the market participants. The ISO will make transaction with some GENCOS for system regulation.

In this work, group concept has been used which describes a collection of buyers, sellers and brokers who function together in some consistent manner.

2.3 Mathematical Formulation of Optimal Power Dispatch Problem

2.3.1 General Formulation

The purpose of the optimal power dispatch problem in an open access environment is to minimize deviations from transaction requests made by market participants. The ideal of open transmission access is to make possible all transactions without curtailments arising from operating constraints. But, in reality, power flow equations and operating constraints must also be satisfied at the same time. Thus, new set of transactions is the closest point near the desired transactions within the security region.

A general mathematical formulation of the optimal dispatch [32] can be written as

$$\text{Min } f(u,x) = [(u-u^0)^T A].W.[(u-u^0)^T A]^T \quad \text{.....(2.1)}$$

Subject to system operating constraints.

$$g(u,x) = 0 \quad \text{........(2.2)}$$

$$h(u,x) \le 0 \quad \text{...... (2.3)}$$

where,

W = A diagonal matrix whose elements are "willingness-to-pay" price premium to avoid transaction curtailment.

u = Set of control variables, which are active powers injected or extracted at generator buses and load buses, respectively, in the present formulation.

u_0 = Desired value of u (in case of firm contract $u = u_0$)

x = Set of dependent variables

A = Constant matrix reflecting curtailment.

Equation (2.2) represents a set of contracted transactions relationship and the system power flow equations, where as equation (2.3) represents the usual set of system operating constraints, including line flow limits.

The line flow (current magnitude) limit (I_i) has been represented, in this work, as a function of real power generations (PG_j) using generalized generation distribution factors as given in [20] which are as following:

$$I_i = \sum_{j=1}^{Ng} D_{ij} PG_j \qquad i = 1,2,\ldots\ldots N_L \qquad \ldots(2.4)$$

Where, Ng is the number of generators and N_L the number of lines.

The state variables have been taken as the real power transactions. The above optimization problem has been solved using the sequential quadratic programming.

2.3.2 Balance Equations under Transactions

Consider a power network consisting of n buses, with 1,2,….,m assumed to be generator buses and m+1,….,n load buses. For simplicity it is assumed that the total transmission losses are made good only out of the injected power at bus-1 under a system regulation transaction between the ISO and the GENCO at bus-1. Hence bus-1 is chosen as the slack bus. The firm power transactions are either bilateral transactions or multilateral transactions with the different curtailment strategy.

The real power generation P_i at generator bus i and active load D_j at load bus j can be defined as follows:

$$P_i = \sum_{j=m+1}^{n} PB_{ij} + \sum_{k=1}^{K} PM_{ik} \qquad i = 2,3,\ldots\ldots,m \qquad \ldots\ldots(2.5a)$$

$$D_j = \sum_{i=1}^{m} DB_{ji} + \sum_{k=1}^{K} DM_{jk} \qquad j = m+1,\ldots..,n \qquad \ldots\ldots\ldots(2.5b)$$

and

$$P_1 = \sum_{j=m+1}^{n} PB_{1j} + \sum_{k=1}^{K} PM_{1k} + P_L \qquad \ldots\ldots\ldots..(2.6)$$

Where,

K = The number of multilateral transfers

PB_{ij} = Injected power at bus i due to an individual contract with a customer at bus j

PM_{ik} = Injected power at bus i under the kth group transfer contract

DB_{ji} = Power taken at bus j under an individual contract with a seller at bus i

DM_{jk} = Power taken at bus j under the kth group transfer contract

P_L = Total real power transmission losses.

Power balance equations in individual (bilateral) contracts are:

$$PB_{ij} = DB_{ji} \quad i = 1,\ldots,m, \quad j = m+1,\ldots,n \qquad \ldots..(2.7)$$

and the group balance equations can be written as,

$$\sum_{i=1}^{m} PM_{ik} = \sum_{j=m+1}^{n} DM_{jk} \quad k=1,\ldots,K \qquad \ldots\ldots\ldots..(2.8)$$

In this power flow problem, generator buses (except bus 1) and load buses can still be taken as P-V and P-Q buses, respectively. Therefore, the real and reactive power flow equations can be written in the general form as

$$g(u,x) = 0 \qquad \ldots\ldots\ldots..(2.9)$$

In the above u will contain either the variables PB_{ij} or DB_{ji} and a certain number of variables from the set { PM_{ik}, DM_{jk} }.

2.3.3 Restriction of Transactions in Case of Congestion

The following four types of transactions curtailment strategies are assumed to be implemented by the ISO in collaboration with market participants in the proposed optimal transmission dispatch model. The active injected power blocks are used as control variables in the following discussions.

1.Curtailment for firm power transactions: In this, case no curtailment is suggested. The power equations for firm transactions will be given by

$$PB_{ij} = PB_{ij}^{0} \qquad \ldots\ldots\ldots.(2.10)$$

$$DB_{ji} = DB_{ji}^{0} \qquad \ldots\ldots\ldots.(2.11)$$

$$PM_{ik} = PM_{ik}^{0} \qquad \ldots\ldots\ldots\ldots.(2.12)$$

$$DM_{jk} = DM_{jk}^{0} \qquad \ldots\ldots\ldots\ldots\ldots.(2.13)$$

Where,

PB_{ij}^{0} = Desired value of the PB_{ij}

DB_{ji}^{0} = Desired value of the DB_{ji}

PM_{ik}^{0} = Desired value of the PM_{ik}

DM_{jk}^{0} = Desired value of the DM_{jk}

2. *Point to Point Curtailment Strategy:* This strategy concerns individual (bilateral) power contracts. As the term suggests, if there is an individual contract, say $\{PB_{ij}, DB_{ji}\}$, the curtailment of PB_{ij} must be the same as the curtailment of DB_{ji}.

The objective function of the optimal dispatch model will be to

$$\text{Min } f1(u,x) = \sum_{i=1}^{m} \sum_{j=m+1}^{n} [W1_{ij}.(PB_{ij} - PB_{ij}^{0})^{2}] \qquad .....(2.14)$$

Where

$W1_{ij}$ = Willingness to pay factor to avoid curtailment of the individual contract $\{PB_{ij}, DB_{ji}\}$

3. *Group Curtailment:* One of the possible group curtailment strategies is to make group transfer without curtailment, even if individual generators within the group or utility have to be re-scheduled. The objective function is to:

$$\text{Min } f2(u,x) = \sum_{k=1}^{K} [W2_{k}.(\sum_{i=1}^{m} PM_{ik} - \sum_{i=1}^{m} PM_{ik}^{0})^{2}] \qquad ...(2.15)$$

Where,

$W2_{k}$ = Willingness to pay factor to avoid curtailment of the kth group transfer

There has to be some way in which group curtailments, when needed, can be distributed among the participants of a group. The group curtailment relationship can be written:

$$DM_{jk} = M_{jk}(PM_{1k}, ..., PM_{mk}) \ \ j = m+1, ..., n; \ k = 1, ..., K \qquad ....(2.16)$$

where $M_{jk}()$ is a function of $PM_{1k}, ..., PM_{mk}$

This implies that if the power supplies PM_{ik} within a group have to be curtailed, this shortfall has to be spread across the loads DM_{jk} in accordance with some agreed formula.

4. *Separate Curtailment:* This is the second basic strategy for group transfers. The concern of this strategy is to minimize the change to every injected or extracted power block at the generator bus and load bus of a group based on willingness to pay factors while (2.8) and (2.16) are satisfied. Therefore, the objective function is to:

$$\text{Min } f3(u,x) = \sum_{k=1}^{K}\sum_{i=1}^{m}[W2_{ik}.(PM_{ik} - PM_{ik}^{0})^2] \qquad \text{...........(2.17)}$$

Where,

$W2_{ik}$ is the willingness to pay factor to avoid curtailment of the injected power block PM_{ik}

There may be more curtailment strategies that are derived from the above four basic strategies. From the above, it also follows that equations (2.1) to (2.17) gives a typical mathematical optimization model. It should be noted that only a certain number of buses of the system will have membership of any particular group.

2.3.4 Computational Steps

Major computational steps involved in OPD for congestion management are as follows:

Step1: Assemble system data and form [Y-Bus] matrix.

Step2: Ascertain power system congestion under the desired market transactions as given below:

Compute the injected power at each bus, except the slack bus, given by the following equations,

For generator buses,

$$P_i = \sum_{j=m+1}^{n} PB_{ij}^{0} + \sum_{k=1}^{K} PM_{ik}^{0} \qquad i = 2,3,\ldots,m; \qquad \text{...........(2.18)}$$

For load buses, the injected power at bus j is the negated value of the D_j given as,

$$D_j = \sum_{i=1}^{m} DB_{ji}^{0} + \sum_{k=1}^{K} DM_{jk}^{0} \qquad j = m+1,\ldots,n; \qquad \text{.............(2.19)}$$

Injected reactive power at the load bus is taken as the negated value of the reactive power load. Using the above loading conditions a base load flow is run and flows in all the line I_k^2 (current magnitude square in kth line connected between buses i and j,) given by the following equation are computed

$$I_k^2 = /(V_i - V_j).Y_{serk}/^2 \qquad k = 1,\ldots,N_L \qquad \text{..........(2.20)}$$

Where,

V_i = Complex voltage at bus i

V_j = Complex voltage at bus j

Y_{serk} = Series admittance of kth line

Compare the actual line flows I_k^2 with the corresponding rated line flow I_{krated}^2 if for all the lines

$$I_k^2 \le I_{krated}^2 \qquad \text{..........(2.20a)}$$

Then, stop, otherwise go to step (3).

Step 3: Compute the generalized generation distribution factors given by equation (2.4), using sensitivity method described in [20].

Step 4: Consider an objective function, as applicable, out of equations, (2.14), (2.15) and (2.17). Take PB_{ij} and PM_{ik} as variables. Consider the nonlinear constraints given by equation (2.20a), only for the overloaded lines. The linear constraints are given by the following equations.

$$\sum_{i=1}^{m} PM_{ik} \le \sum_{i=1}^{m} PM_{ik}^{0} \qquad k = 1,\ldots, K; \qquad \text{.............(2.21)}$$

Where, K is the number of multilateral transfers.

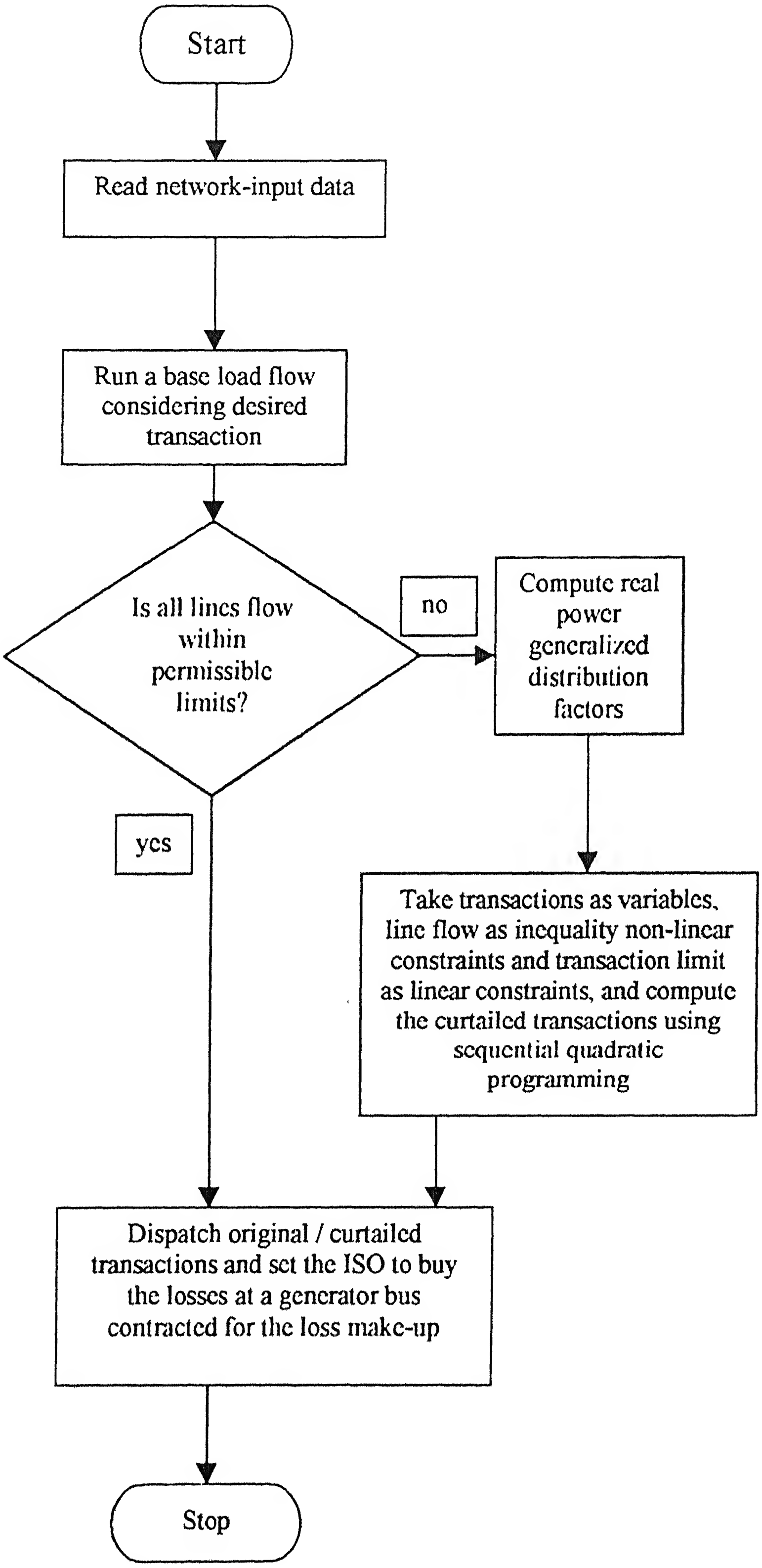
Compute the curtailed transactions PB_{ij} and PM_{ik} using sequential quadratic programming. Spread the group curtailment as given by equation (2.16).

Based on the above calculated values of original / curtailed active power transfers the ISO will decide to buy the required regulating power at a generator bus contracted for loss make-up. A flow chart shown in fig.2.1 gives the major steps involved in the above optimal power dispatch model.

2.4 Study Results

The study has been conducted on the IEEE-14 bus and UPSEB-75 bus systems, slightly modified to represent deregulated market situation. The details of these systems are given in the Appendix-A and B, respectively. For the present study, reactive power demand at load buses has been taken to remain constant. The losses are assumed to be supplied, only by the generator at bus-1 in both the systems.

Fig. 2.1: Flowchart showing the major steps in OPD



2.4.1 IEEE-14 Bus Test System

Fig.A.1 shows the modified IEEE-14 bus test system. This system has five reactive power sources including four real power generators and one synchronous condenser. It has 20 lines. The generators and loads data including the MVAR limits of the generators, are shown in table A.1. Transformer and line data are provided in table A.2 and A.3, respectively. The line ratings in terms of square of the current flow (I^2 in p. u.) are given in table 2 2. Bus-1 is chosen as slack bus.

Two groups of multilateral contracts have been considered. Group-1 makes power transfers from buses 2 and 4 to buses 7, 9, 11, 12 and 14 and group-2 makes transfers from bus 3 to buses 6, 10 and 13. Table 2.1 presents desired generation and load data of these two groups. In a separate study, three bilateral contracts have been considered between generator bus 3 and load bus-6, generator bus-3 and load bus–10, and generator bus –3 and load bus -13. Further, a case of firm contract between generator bus-3 and load bus-10 has been studied. If the desired power transactions are dispatched without curtailment, the transmission line-10 between buses 4 & 11 will be overloaded. The loading pattern of the lines under the desired transaction dispatch is shown in table 2.2. From this table it can be seen that loading of line 10 is 0.3222 p. u. against line rating of 0.25 p. u. Therefore, the ISO has to curtail the initial power transfers in order to operate the system within security limits. Six different strategies for curtailment of transactions, as given below, were employed to bring the line flows within limits.

1(a). The spreading of curtailment of the loads in each group, given by eq. (2.16), has been assumed to be linear and takes the following form.

$$DM_{jk} = DM^0_{jk}.(\sum_{i=2}^{4} PM_{ik} / \sum_{i=2}^{4} PM^0_{ik}) \qquad \text{..............(2.22)}$$

Both the group employ the groups curtailment strategy as given by eq. (2.15) and all the willingness to pay premium (diagonal elements of matrix W) are taken to be equal say 1∀/MWh (∀ stands for an arbitrary unit of currency).

1(b). Same as case 1(a) but the willingness to pay price premium to avoid curtailment on group 1 is assumed to be 3 times as compared to group 2

1(c). In this case, group 1 selects the separate curtailment strategy given by eq. (2.17) for each generator. The willingness to pay price premium for generated power at bus 4 in group-1 is set three times that of bus 2. Load curtailment strategy is same as in the case 1(a).

1(d). Group 2 abandons the group curtailment strategy given by eq. (2.15) and adopts the point to point curtailment strategy given by eq. (2.14) for the individual (bilateral) contracts (3-6, 3-10, and 3-13). The strategy for group-1 is considered same as in case 1(a).

1(e). Same as case 1(d) except that the price premium to avoid curtailment on the individual contract 3-10 is increased to 3 times of the other two bilateral contracts.

1(f). Same as case 1(d) except that the individual contract 3-10 has been taken as firm contract. Thus, curtailment in group-2 shall affect only 3-6 and 3-13.

Optimal power dispatch results for the above six cases are shown in table-2.3. In case 1(a), all power deliveries are curtailed in varying amount and the total transaction is reduced to 445.46 MW as against the total desired transaction of 469.80 MW. Case 1(b) shows that a higher premium price of willingness to pay benefits group-1 very modestly (less than 0.25 MW) but causes severe curtailment in group-2 (about 8 MW), hence, decreases the total transaction. Case 1(c) shows that when in group-1 the willingness to pay has been increased at generator bus-4 only, there is a slight increase in its output but considerable reduction in the output power of generator at bus-2. In case 1(d), due to abandonment of group curtailment strategy, the load in group-2 at bus-10 is effected badly, even though the willingness to pay value remains the same. In case 1(e), by raising the willingness to pay price premium for load at bus-10, the load at this bus is partly restored. In case 1(f), since the load at bus-10 has been taken to be firm, any curtailment in group-2 has effected the loads at bus-6 and 13. The load at bus-6 is worst affected, and the total power transaction is minimum (434.36 MW) as compared to all the other cases.

2.4.2 UPSEB-75 Bus System

Data for UPSEB-75 bus system is taken from [35]. Fig.B.1 shows this system with buses renumbered. For the sake of simplicity, any two lines with the same specifications connected between two particular buses is considered as single line with the equivalent series impedance and shunt susceptances. This system has 15 real and reactive power generators and 95 lines. The generators and reactive load data including the MVAR limits of the generators are shown in table B.1 and B.2. Transformer and line data are provided in tables B.3 and B.4, respectively. The line flow limits in terms of square of current flow (I^2 in p. u.) are given in table 2.5. Bus-1 is chosen as slack bus.

Various groups of multilateral, bilateral and firm contracts have been assumed. Generation and load combination in a particular group is made based on the geographical locations. The generation at 15 buses is considered to have contracts with the load buses in the following three patterns.

2.4.2.1 Pattern –1

In pattern-1, the following different types of transactions have been considered.

Multilateral Transaction-1: In this group (called as group-1) power transfers from generator buses 1, 2, 3, 9, 11and 12 to load buses 20, 25, 27, 37, 42, 46, 47, 48, 49, 50, 51, 52, 56, 60, 64, 66, 67, 68, 70, 71, 72 and 74 have been considered. The desired transactions of this group transfer are shown in table 2.4.1. It is the largest power transaction contract with 3440.6 MW of desired power transfer.

Multilateral Transaction-2: In this group (called group-2), power transfers from generator buses 4,10,13 and 15 to load buses 24, 28, 54, 55, 61, 63, 65 and 73 are considered. The desired transaction of this group transfer is shown in table 2.4.2. In this group, the total desired transaction is 1548.0 MW.

Multilateral Transaction-3: In this group (called group-3), power transfers from generator buses 5, 6, 7 and 14 to load buses 30, 32, 39 and 62 is considered. The

desired transaction of this group transfer is shown in table 2.4.3. In this group, the total desired transaction is 490.0 MW.

Bilateral Transaction-1: In this transaction a one to one transfer of power from generator bus 8 to load bus 34 is considered. The desired bilateral power transfer is 81.0 MW. Table 2.4.4 shows the relevant information of this transaction.

Firm Transaction: The loads at the buses 16 and 75 are negative due to DC links or fixed generation. The negative loads at bus 16 making bilateral power transfer to load at bus 69 and negative load at bus 75 is considered to make a multilateral firm power transfers to load buses at 53, 57, 58 and 59. Relevant data of the firm power transfers is shown in table 2.4.5.

Under pattern 1, if the total desired power transaction of 6059.6 MW is dispatched without curtailment, the transmission lines 4, 36 and 89 get overloaded. The loading pattern of transmission lines under desired transaction dispatch is shown in table 2.5. From this table, it can be seen that the loading of line-4 connected between buses 23 and 24 is 23.445 p u. against line rating of 23.04 p. u., that of line-36 connected between buses 27 and 51, is 2.643 p. u. against line rating of 2.25 p. u. and that of line-89 connected between buses 55 and 44, is 10.196 p. u. against line rating of 9.0 p. u. Therefore, the ISO has to curtail the initial power transfers in order to operate the system within security limits. Seven different strategies for curtailment of transaction, as given below, were employed to bring the line flow within limits.

2(a). The curtailment on all the multilateral contracts is based on group curtailment strategy as given by eq. (2.15) and the group curtailment relationships given by eq. (2.16) for the multilateral transactions take the simple linear form

$$DM_{jk} = DM_{jk}^{0} . (\sum_{i=1}^{15} PM_{ik} / \sum_{i=1}^{15} PM_{ik}^{0}) \qquad k = 1, 2, 3 \qquad \text{..........(2.23)}$$

The point to point curtailment strategy given by eq. (2.14) is employed by the bilateral transaction. For firm transaction, no curtailment is employed. All the willingness to pay premium (diagonal elements of matrix W) are taken to be equal say 1∀/MWh (∀ stands for an arbitrary unit of currency).

2(b). Same as 2(a) but willingness to pay price premium to avoid curtailment on multilateral transaction-1 is increased to three times.

2(c). Same as 2(a) but willingness to pay price premium to avoid curtailment on multilateral transaction-2 is increased to three times.

2(d). Same as 2(a) but willingness to pay price premium to avoid curtailment on multilateral transaction-3 is increased to three times.

2(e). Same as 2(a) but willingness to pay price premium to avoid curtailment on bilateral transaction is increased to three times.

2(f). Same as 2(a) but willingness to pay price premium to avoid curtailment on multilateral transaction-2 and 3 together is increased to three times.

2(g). Same as 2(a) but willingness to pay price premium to avoid curtailment on multilateral transaction-1 and 2 together is increased to three times.

Optimal power dispatch results for the above seven cases are shown in tables 2.6.1 – 2.6.5. Tables 2.6.1, 2.6.2 and 2.6.3 show the optimal power dispatch results of the above seven cases for multilateral transactions 1, 2 and 3, respectively. Table 2.6.4 shows the optimal power dispatch results of the bilateral transaction-1 of the above cases. In case of firm transaction, there is no curtailment in the initial contracted power, as it has not been felt necessary to curtail firm power transactions to avoid congestion in the transmission system. Table 2.6.5 shows the summary of the various transactions and the total system losses in each of the above cases.

In case 2(a), all power deliveries except firm transactions are curtailed in varying amount and the total transaction is reduced to 5468.011 MW as against the total desired transaction of 6059.6 MW. Multilateral transaction-1 is 56.779 % of the total desired transaction. In case 2(b), a higher premium price of willingness to pay benefits multilateral transaction-1 very modestly (less than 4.0 MW) but causes severe curtailment in all other multilateral and bilateral transactions. Bilateral transaction has reduced to its minimum generation level and become as low as 10 % of its desired value. The total transaction in case 2(b) is reduced by 233.85 MW as compared to case 2(a). In case 2(c), a higher premium price of willingness to pay benefits multilateral transaction-2 extensively (by 153.745 MW). At the same time it does not cause any severe curtailment to the other multilateral and bilateral

transaction groups, resulting in increment of the total transaction by 146.101 MW as compared to case 2(a). In case 2(d), a higher premium price of willingness to pay benefits multilateral transaction-3 considerably (by 76.399 MW i.e 20.33 %) and at the same time it does not cause any curtailment to any other multilateral and bilateral transaction groups. In case 2(e), a higher premium price of willingness to pay benefits bilateral transaction considerably (by 16.427 MW i.e. 29.15 %) and causes hardly any curtailment to other multilateral groups. In case 2(f) a higher premium price of willingness to pay benefits multilateral group-2 and 3 together to a great extent (by 153.889 MW i.e. 11.69 % and 75.742 MW i.e. 20.16 % respectively). At the same time it does not cause any severe curtailment to other multilateral and bilateral transaction groups, resulting in increment of the total power transaction by 224.10 MW as compared to case 2(a). In case 2(g) a higher premium price of willingness to pay to one big multilateral contract (i.e.1) and to one small contract (i.e.2) simultaneously, benefits multilateral transaction group-1 modestly by (+0.024MW) but affects adversely (by-0.091MW), though modestly, to the multilateral transaction group-2 as compared to the case 2(a). At the same time it affects very adversely the other multilateral and bilateral transaction groups, where the premium price of willingness to pay is not increased. Out of these, the bilateral transaction has been affected most adversely and went as low as to its minimum generation limit of 8 MW as against its desired value of 81 MW.

2.4.2.2 Pattern –2

In this pattern, the desired generation and loads are kept same as in the pattern-1. However, the load at bus 56, which was part of multilateral group-1, is assumed to form a separate bilateral transaction group and is fed from the generator at bus-1. In this pattern the new generation and load combinations are as following.

Multilateral Transaction-1: In this group (group-1), power transfers from generator buses 1, 2, 3, 9, 11and 12 to load buses 20, 25, 27, 37, 42, 46, 47, 48, 49, 50, 51, 52, 60, 64, 66, 67, 68, 70, 71, 72 and 74 have been considered. The desired transactions of this group transfer are shown in table 2.7.1. It is again the largest power transaction contract with 3300.32 MW desired power transfer.

Multilateral Transaction-2 &3: Multilateral transactions 2 & 3 in this pattern are same as multilateral transactions 2& 3 in pattern-1, respectively.

Bilateral Transaction-1: Bilateral transaction-1 in the pattern-2 is same as the bilateral transaction-1 in pattern-1.

Bilateral Transaction-2: In this transaction a one to one transfer of power from generator bus-1 to load bus 56 is considered. The desired bilateral power transaction is 140.28 MW. Table 2.7.2 shows the relevant information about this transfer.

Firm Transaction: It is same as the firm transaction in pattern-1.

If the desired power transactions are dispatched without curtailment, the transmission system gets overloaded in the similar way as in pattern-1. The loading pattern of transmission lines under desired transaction dispatched is same as shown in table 2.5. To avoid the congestion of the transmission system, ISO has to curtail the initial power transfers in order to operate the system within security limits. Five different strategies for curtailment of transactions, as given below, were employed to bring the line flow within limits.

3(a). The curtailment strategy to all the multilateral groups 1 to 3 is same as for the respective multilateral group in case 2(a). The curtailment strategy to both the bilateral transactions 1 and 2 is also same as for the bilateral transaction-1 in case 2(a). For firm transaction no curtailment is employed. All the willingness to pay premium (diagonal elements of matrix W) are taken to be equal say 1∀/MWh (∀ stands for an arbitrary unit of currency).

3(b). Same as 3(a) but willingness to pay price premium to avoid curtailment on bilateral transaction-2 is increased to three times.

3(c). Same 3(a) but willingness to pay price premium to avoid curtailment on both the bilateral transaction1 and 2 is increased to three times.

3(d). Same as 3(a) but willingness to pay price premium to avoid curtailment on biggest multilateral transaction-1 and on bilateral transaction-2 is increased to three times.

3(e). Same as 3(d) but willingness to pay price premium to avoid curtailment on bilateral transaction-2 is further increased to two times.

Optimal power dispatch results for the above five cases are shown in tables 2.8.1 – 2.8.6. Tables 2.8.1, 2.8.2 and 2.8.3 show the optimal power dispatch results of the above five

cases for multilateral transactions 1, 2 and 3, respectively. Table 2.8.4 and 2 8.5 show the optimal power dispatch results of the bilateral transactions-1 and 2, respectively for the above cases. In case of firm transaction, there is no curtailment in the initial contracted power, as it has not been felt necessary to curtail firm power transactions to avoid congestion in the transmission system. Table 2.8.6 shows the summary of the various transactions and the total system losses in each of the above cases.

In case 3(a) all power deliveries except firm power transaction are curtailed in varying amount and the total power transactions is reduced to 5414.792 MW as against the total desired transaction of 6059.6 MW. Comparing cases 2(a) and 3(a), though the willingness to pay price premium value are same for the two cases, the following points were observed.

I. There is a heavy reduction of transmitted power at bus-56 after entering into a separate bilateral group, which is 131.265 MW in case of 2(a) and only 14.0 MW in case of 3(a).

II. There is a reduction of power transaction in multilateral group-1 in case of 2(a) i.e. from 3219.489 MW to the case-3 (a) having combined multilateral group-1 and bilateral group-2 i.e. 3119.832 MW (3105.832+14.0 MW).

III. There is a considerable gain in the power transfer of multilateral groups-2 & 3 and bilateral group-1 in case 3(a) as compared to the respective power transfers in case 2(a).

IV. The total power transaction in case-3 (a) has reduced to 5414.792 MW as compared to case -2(a), which was 5468.011 MW.

In case 3(b) a higher premium price of willingness to pay benefits transmitted power at bus-56 (bilateral group-2) to a great extent as compared to 3(a) i.e. increased by more than five times (from 14.0 MW to 72.414 MW) but not as higher as in case 2(a) which is 131.265 MW. Further, in case 3(b) there is a marginal reduction in multilateral transaction groups-1 to 3 and bilateral group-1, but there is an overall improvement in the total power transaction as compared to 3(a) (from 5414.792 MW to 5448.055 MW). In case 3(c), a higher premium price of willingness to pay to both the bilateral groups-1 & 2 benefits both of these bilateral transactions considerably. But it causes modest reduction in all the multilateral groups 1-3, resulting in the overall increment in the total transaction (5414.792

MW to 5466.448 MW) as compared to case 3(a). Further, comparing cases 3(b) and 3(c), it is seen that all the transactions are better off (increased) in case 3(c) than 3(b). In case 3(d), a higher premium price of willingness to pay by the bigger multilateral transaction-1 and bilateral transaction-2, together benefits modestly only the multilateral transaction-1 and does not cause any improvement in the bilateral transaction-2. At the same time, it causes heavy curtailments in all the other multilateral transaction 2 & 3 and bilateral transaction-1 as compared to 3(a). Bilateral transaction-1 is worst affected in this case and the total transaction has been reduced to as low as 5142.933 MW. In case 3(e), a further higher premium price of willingness to pay by bilateral transaction-2, as compared to 3(d), is able to recover the bilateral transaction-2 up to some extent (i. e. from 14.0 MW to 42.68 MW) but causes no improvement in the other transactions. Rather, it worsens the transaction of bilateral contract-1 (from 16.832 MW to 15.433 MW).

2.4.2.3 Pattern –3

From the patterns 1 & 2 above, it is seen that when the total desired power transaction of 6059.6 MW are dispatched, the transmission lines 4 connected between buses 23 and 24, line-36 connected between buses 27 and 51 and line-89 connected between buses 55 and 44 are getting overloaded. From the transmission network shown in fig. B.1, it can be seen that line 36 is connected as radial feeder. A part of the relevant UPSEB-75 bus system is reproduced in fig.- 2.2. The power flows from bus 27 to 51 and bus 51 to 52, as there is no generator at either bus-51 or bus-52.

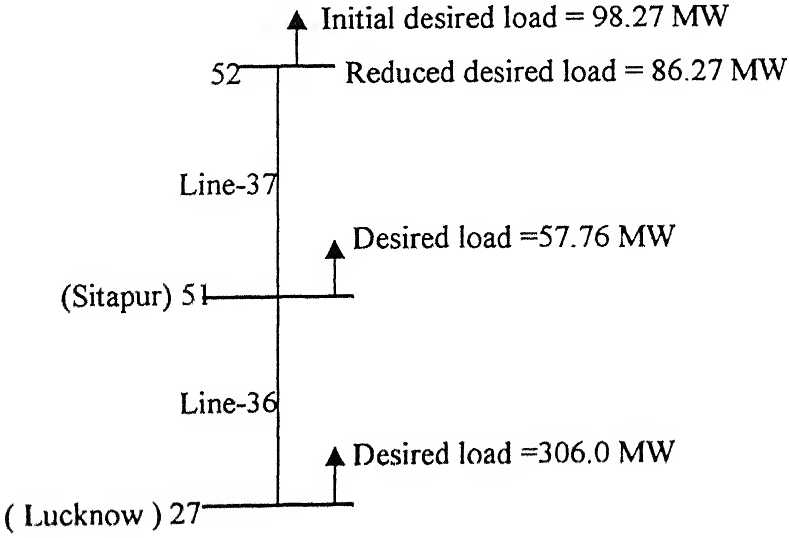


Fig 2.2: A part of the 75-bus UPSEB system

Hence, if the desired loads at bus-51 or at bus-52 or at both are reduced, it may help in relieving the congestion in the transmission line-36. The pattern-3 is simulated similar to the pattern-1 given in 2.4.2.1 with a reduced load requirement at bus-52, so as to avoid the transmission congestion at line-36 connected between buses 27 and 51. By reducing the load in phased manner, it is found that with a reduction of desired load of 12 MW at bus 52 and a total revised transaction of 6047.6 MW as against the initial total transaction of 6059.6 MW in pattern 1 & 2, the transmission line-36 is relieved of the congestion. The loading pattern of transmission lines under this dispatch is shown in table 2.5. However lines-4 and line-89 are still overloaded.

All the desired power transfers in case of multilateral transaction-1 under pattern-3 are same as for the pattern-1 except the load requirement at bus-52, is reduced. The revised desired transactions of this group are shown in table 2.9. The total desired power transaction is now 3428.6 MW.

Multilateral transaction 2 & 3, bilateral transaction, firm transaction in this pattern-3 is exactly same as those in the pattern-1.

ISO has to curtail the initial power transfers to avoid congestion on transmission lines-4 & 89 and to operate the system in a secure state.

A curtailment strategy as case 4 is employed exactly similar to case 2(a). Optimal power dispatch results for this case is shown in table 2.10.1 to 2.10.5. Tables 2.10.1-2.10.3 show the OPD results of the case-4 for the multilateral transactions 1-3, respectively. Table 2.10.4 shows the OPD of the case 4 for the bilateral transaction-1. Table 2.10.5 shows the summary of the various transactions and the total system losses in each of the above cases. Comparing the case 4 with case 2(a) the following points are observed.

I. The curtailment in the various transactions is modest or nil in case 4.

II. In case 4, the load transacted at bus-52 is 86.072 MW as against 91.955 MW in case 2(a), which is approximately 6.0 MW less.

III. Total real power transaction is much higher i.e. 5996.384 MW in case 4 as compared to 2(a) i.e. 5468.011 MW. There is an increment of 538 MW of the total power transaction.

Table 2.1:Desired Transactions (IEEE-14 bus test system).

Bus number	Desired generation & load (MW)
Group-1	
Gen-2	**157.7**
Gen-4	**98.0**
Load-7	102.9
Load-9	57.8
Load-11	53.5
Load-12	16.1
Load-14	25.4
Group-2	
Gen-3	**214.1**
Load-6	167.8
Load-10	19.0
Load-13	27.3
Total transaction (Gen. 2+3+4)	469.8

1.Generation is shown in bold letters.

2. Loads are shown in normal letters.

3. Generator at bus-1 is for loss Make-up only.

Table 2.2: Effect of Desired Transaction Dispatch on Line Flow
(IEEE-14 bus test system)

Line no.	Starting bus	End bus	Line rating (I^2) p.u.	Line loading I^2 in (p.u.)
1	4	6	0.4225	0.1653
2	7	8	0.4225	0.2990
3	7	9	0.1600	0.0854
4	1	2	2.9241	0.1502
5	1	7	2.9241	0.4956
6	2	3	2.9241	0.9797
7	2	6	2.9241	1.0366
8	2	7	2.9241	1.0753
9	3	6	2.9241	1.1080
10	**4**	**11**	**0.2500**	**0.3222**
11	4	12	0.2500	0.0370
12	4	13	0.2500	0.1895
13	5	8	0.2500	0.0858
14	6	7	2.9241	0.0525
15	8	9	0.4225	0.2677
16	9	10	0.2500	0.0295
17	9	14	0.2500	0.0096
18	10	11	0.2500	0.0016
19	12	13	0.2500	0.0010
20	13	14	0.2500	0.0374

Note: Overloaded line is shown in bold letters.

Table 2.3: Results of OPD (IEEE-14 bus test system).

Bus number	Constrained generation & load (MW)					
	Case-1(a)	Case-1(b)	Case-1(c)	Case-1(d)	Case-1(e)	Case-1(f)
1(loss make-up)	27.896	26.732	26.248	26.778	26.965	26.137
Group-1						
Gen-2	**157.7**	**157.7**	**150.91**	**157.7**	**157.7**	**150.584**
Gen-4	**77.8**	**78.046**	**81.263**	**79.702**	**77.591**	**80.459**
Load-7	94.771	94.87	93.432	95.537	94.687	92.978
Load-9	53.234	53.289	52.482	53.664	53.187	52.226
Load-11	49.274	49.325	48.577	49.672	49.23	48.431
Load-12	14.274	14.844	14.619	14.948	14.815	14.548
Load-14	23.394	23.418	23.063	23.582	23.373	22.951
Group-2						
Gen-3	**209.96**	**201.836**	**203.813**	**202.854**	**204.344**	**203.319**
Load-6	164.557	158.188	159.74	164.051	163.619	158.528
Load-10	18.633	17.912	18.087	15.251	17.606	19.0
Load-13	26.772	25.736	25.988	23.551	23.119	25.791
Total trans. (Gen.2+3+ 4)	445.46	437.582	435.986	440.256	439.635	434.362

Table 2.4.1: Desired Value of Multilateral Transaction-1
(UPSEB-75 bus system), Pattern-1

S. No.	Generators bus no.	Generation (MW)	S. No.	Load bus no.	Load (MW)
1.	1	541.6	1	20	156.37
2.	2	260.0	2	25	210.48
3.	3	180.0	3	27	306.00
4.	9	550.0	4	37	144.28
5.	11	109.0	5	42	1000.0
6.	12	1800.0	6	46	156.34
			7	47	74.55
			8	48	50.83
			9	49	85.72
			10	50	202.10
			11	51	57.76
			12	52	98.27
			13	56	140.28
			14	60	74.20
			15	64	56.79
			16	66	31.74
			17	67	96.43
			18	68	42.87
			19	70	23.34
			20	71	91.73
			21	72	52.52
			22	74	288.00
Total		3440.60	Total		3440.60

Table 2.4.2: Desired Value of Multilateral Transaction-2
(UPSEB-75 bus system), Pattern-1, 2 & 3

S. No.	Generators bus no.	Generation (MW)	S. No.	Load bus no.	Load (MW)
1	4	107.0	1	24	220.0
2	10	87.0	2	28	120.0
3	13	900.0	3	54	160.0
4	15	454.0	4	55	270.0
			5	61	105.0
			6	63	58.0
			7	65	145.0
			8	73	470.0
Total		1548.0	Total		1548.0

Table 2.4.3: Desired Value of Multilateral Transaction-3
(UPSEB-75 bus system), Pattern-1, 2 & 3

S. No.	Generators bus no.	Generation (MW)	S. No.	Load bus no.	Load (MW)
1	5	180.0	1	30	226.59
2	6	110.0	2	32	78.11
3	7	60.0	3	39	85.12
4	14	140.0	4	62	100.18
Total		490.0	Total		490.0

Table 2.4.4: Desired Value of Bilateral Transaction-1
(UPSEB-75 bus system), Pattern-1, 2 & 3

S. No.	Generators bus no.	Generation (MW)	S. No.	Load bus no.	Load (MW)
1	8	81.0	1	34	81.0

Table 2.4.5: Desired Value of Firm Transactions

(UPSEB-75 bus system), Pattern-1, 2 & 3

S. No.	Bus no.	Load (MW)	S. No.	Bus no.	Load (MW)
Bilateral firm transaction	16	-56.0	1	69	56.0
Multilateral firm transaction	75	-444.0	1	53	82.0
			2	57	150.0
			3	58	94.0
			4	59	118.0
Total		-500.0	Total		500.0

Table 2.5: Effect of Desired Transaction Dispatch on Line Flow

(UPSEB-75 bus system), Pattern-1, 2 & 3

Line No.	Starting bus	End bus	Line rating I^2 (in p. u.)	Line loading I^2 (in p. u.)	
				When total transaction is 6059.6 MW(pattern 1&2)	When total transaction is 6047.6 MW(pattern 3)
1	19	20	23.040	7.734	7.723
2	17	16	23.040	6.459	6.275
3	22	25	23.040	12.687	12.663
4	**23**	**24**	**23.040**	**23.445**	**23.045**
5	26	27	23.040	14.810	14.281
6	29	30	51.840	41.570	41.483
7	36	37	23.040	3.101	3.105
8	38	39	5.760	1.098	1.097
9	45	44	39.690	2.271	2.298

10	16	2	22.278	6 668	6.642
11	18	3	23.040	3.630	3.615
12	17	1	92.160	51 349	49.304
13	28	4	3.422	1.150	1.145
14	31	5	7.618	2.992	2.990
15	32	6	1.538	1.114	1.113
16	33	7	1.000	0.334	0.333
17	34	8	6.250	1.035	1.033
18	35	9	51.840	29.039	28.968
19	24	10	6.250	0.798	0.782
20	40	11	14.063	1.482	1.463
21	41	12	564.538	297.703	297.555
22	42	13	138.298	74.513	74.478
23	43	14	27.878	2.051	2.035
24	44	15	43.560	20.226	20.231
25	16	46	9.000	4.574	4.452
26	16	50	20.250	13.094	12.839
27	17	19	25.000	15.414	15.082
28	17	23	25.000	8.583	8.307
29	23	29	25.000	10.806	10.749
30	20	64	2.250	0.344	0.343
31	19	26	30.250	7.769	7.409
32	47	50	9.000	2.804	2.706
33	47	67	9.000	0.919	0.897
34	24	27	9.000	0.460	0.362
35	24	54	9.000	8.359	8.369
36	**27**	**51**	**2.250**	**2.643**	**2.233**
37	51	52	2.250	1.056	0.810
38	25	60	2.250	0.556	0.555
39	25	43	2.250	0.014	0.012
40	34	54	9.000	0.010	0.010
41	54	28	9.000	1.259	1.257
42	28	43	3.240	0.051	0.050
43	28	56	9.000	0.631	0.634
44	56	30	9.000	0.014	0.013
45	30	57	3.240	2.062	2.059
46	53	30	3.240	0.689	0.689
47	53	61	2.250	0.002	0.002
48	30	61	2.250	0.157	0.157
49	57	58	3.240	0.001	0.001
50	57	59	3.240	0.008	0.007
51	59	39	2.250	1.525	1.522
52	39	32	2.250	0.178	0.178
53	39	33	9.000	0.359	0.358
54	54	63	2.250	0 077	0.080
55	55	63	3.240	0.248	0.246
56	61	62	2.250	0.407	0.406
57	62	32	9.000	2[illegible]	2.611

58	31	32	12 960	2.994	2.991
59	35	36	25.000	10.264	10 099
60	46	37	2.250	0 228	0.226
61	19	36	25 000	2.749	2.666
62	17	35	36.000	4.967	5.047
63	20	40	9.000	0.119	0.114
64	40	48	2.250	0.630	0.629
65	74	41	25.000	14.364	14.346
66	74	41	25.000	17.768	17.746
67	74	73	25.000	11.670	11.639
68	26	22	25.000	13.262	13.210
69	29	22	30 250	0.206	0.204
70	26	41	25.000	22.928	22.882
71	48	49	2.250	0.085	0.085
72	49	40	2.250	0.495	0.494
73	38	29	30.250	0.565	0.563
74	38	22	30.250	0.350	0.345
75	18	47	12.960	0.186	0.201
76	30	65	12.960	1.223	1.221
77	41	42	36.000	21.634	21.618
78	42	74	25.000	13.605	13.588
79	20	66	2.250	0.115	0.114
80	23	74	144.000	27.216	27.212
81	24	67	12.960	0.010	0.008
82	18	68	3.240	0.847	0.824
83	18	71	2.890	0.522	0.504
84	27	68	2.890	0.196	0.186
85	27	71	3.250	0.046	0.049
86	25	72	2.250	0.581	0.580
87	43	58	2.250	0.910	0.909
88	43	56	9.000	0.267	0.265
89	**55**	**44**	**9.000**	**10.196**	**10.158**
90	73	45	100.000	1.601	1.611
91	29	75	36.000	18.662	18.625
92	37	69	9.000	0.433	0.432
93	70	72	3.240	0.055	0.055
94	21	65	12.250	0.118	0.117
95	21	30	2.250	0.114	0.113

Note: Congested lines are shown in bold letters.

Table 2.6 1: Results of OPD of Multilateral Transaction-1

(UPSEB-75 bus system), Pattern-1

Bus number	Constrained generation & load (MW)						
	Case-2(a)	Case-2(b)	Case-2(c)	Case-2(d)	Case-2(e)	Case-2(f)	Case-2(g)
Generations							
1	**320.489**	**324.160**	**315.275**	**320.583**	**320.432**	**315.325**	**320.513**
2	**260.0**	**260.0**	**260.0**	**260.0**	**260.0**	**260.0**	**260.0**
3	**180.0**	**180.0**	**180.0**	**180.0**	**180.0**	**180.0**	**180.0**
9	**550.0**	**550.0**	**550.0**	**550.0**	**550.0**	**550.0**	**550.0**
11	**109.0**	**109.0**	**109.0**	**109.0**	**109.0**	**109.0**	**109.0**
12	**1800.0**	**1800.0**	**1800.0**	**1800.0**	**1800.0**	**1800.0**	**1800.0**
Loads							
20	146.321	146.488	146.083	146.325	146.320	146.086	146.322
25	196.953	197.178	196.633	196.959	196.952	196.638	196.955
27	286.335	286.661	285.870	286.343	286.332	285.876	286.337
37	135.008	135.162	134.788	135.012	135.007	134.791	135.009
42	935.715	936.801	934.215	935.762	935.727	934.234	935.741
46	146.272	146.459	146.055	146.297	146 292	146.058	146.294
47	69.759	69.839	69.646	69.761	69.758	69.647	69.760
48	47.563	47.618	47.486	47.565	47.563	47.487	47.564
49	80.211	80.303	80.081	80.214	80.210	80.083	80.212
50	189.112	189.327	188.805	189.117	189.110	188.809	189.113
51	54.048	54.110	53.960	54.050	54.048	53.961	54.048
52	91.955	92.059	91.805	91.957	91.954	91.807	91.955
56	131.265	131.414	131.052	131.269	131.264	131.054	131.266
60	69.432	69.511	69.319	69.434	69.431	69.320	69.432
64	53.140	53.201	53.054	53.142	53.140	53.055	53.141
66	29.700	29.734	29.652	29.701	29.700	29.653	29.700
67	90.233	90.336	90.086	90.236	90.232	90.088	90.234
68	40.115	40.161	40.065	40.116	40.115	40.051	40.115
70	21.840	21.865	21.805	21.841	21.840	21.805	21.840
71	85.835	85.933	85.696	85.837	85.834	85.697	85.836
72	49.145	49.201	49.065	49.146	49.144	49.066	49.145
74	269.492	269.799	269.054	269.499	269.489	269.059	269.494
Total transaction (Gen.1+2+3+ 9+11+12)	3219.489	3223.160	3214.275	3219.583	3219.432	3214.325	3219.513

Table 2.6.2: Results of OPD of Multilateral Transaction-2
(UPSEB-75 bus system), Pattern-1

Bus number	Constrained generation & load (MW)						
	Case-2(a)	Case-2(b)	Case-2(c)	Case-2(d)	Case-2(e)	Case-2(f)	Case-2(g)
Generations							
4	**107.0**	**107.0**	**107.0**	**107.0**	**107.0**	**107.0**	**107.0**
10	**87.0**	**87.0**	**87.0**	**87.0**	**87.0**	**87.0**	**87.0**
13	**900.0**	**900.0**	**900.0**	**900.0**	**900.0**	**900.0**	**900.0**
15	**222.397**	**45.0**	**376.142**	**222.902**	**222.377**	**376.286**	**222.306**
Loads							
24	187.085	161.873	208.935	187.157	187.082	208.955	187.072
28	102.046	88.295	113.964	102.085	102.045	113.976	102.039
54	136.062	117.726	151.953	136 114	136.060	151.968	136.052
55	229.604	198.663	256.420	229.692	229.601	256.445	229.588
61	89.290	77.258	99.719	89.325	89.288	99.729	89.285
63	49.322	42.676	55.083	49.341	49.322	55.088	49.319
65	123.306	106.689	137.707	123.353	123.304	137.721	123.297
73	399.682	345.82	446.361	399.835	399.675	446.404	399.654
Total transaction (Gen. 4+10+13+15)	1316.397	1139.0	1470.142	1316.902	1316.377	1470.286	1316.306

Table 2.6.3: Results of OPD of Multilateral Transaction-3
(UPSEB-75 bus system), Pattern-1

Bus number	Constrained generation & load (MW)						
	Case-2(a)	Case-2(b)	Case-2(c)	Case-2(d)	Case-2(e)	Case-2(f)	Case-2(g)
Generations							
5	**180.0**	**180.0**	**180.0**	**180.0**	**180.0**	**180.0**	**180.0**
6	**110.0**	**110.0**	**110.0**	**110.0**	**110.0**	**110.0**	**110.0**
7	**60.0**	**60.0**	**60.0**	**60.0**	**60.0**	**60.0**	**60.0**
14	**25.767**	**14.0**	**23.787**	**102.166**	**25.750**	**101.509**	**14.0**
Loads							
30	173.766	168.324	172.850	209.095	173.757	208.790	168.324
32	59.900	58.025	59.585	72.079	59.898	71.974	58.025
39	65.276	63.232	64.932	78.547	65.273	78.434	63.232
62	76.825	74.419	76.420	92.445	76.822	92.311	74.419
Total transaction (Gen. 5+6+7+14)	375.767	364.000	373.787	452.166	375.750	451.509	364.000

Table 2.6.4. Results of OPD of Bilateral Transaction-1
(UPSEB-75 bus system), Pattern-1

Bus number		Constrained generation & load (MW)						
		Case-2(a)	Case-2(b)	Case-2(c)	Case-2(d)	Case-2(e)	Case-2(f)	Case-2(g)
Gen.	**8**	**56.358**	**8.0**	**55.908**	**56.443**	**72.785**	**55.996**	**8.0**
Load	34	56.358	8.0	55.908	56.443	72.785	55.996	8.0

Table 2.6.5: Summary of Optimal Power Dispatch Results
(UPSEB-75 bus system), Pattern-1

Trans-actions	Desired value (MW)	Constrained value (MW)						
		Case-2(a)	Case-2(b)	Case-2(c)	Case-2(d)	Case-2(e)	Case-2(f)	Case-2(
Multl-1	3440.6	3219.489	3223.16	3214.275	3219.583	3219.432	3214.325	3219.51
Multl-2	1548.0	1316.397	1139.0	1470.142	1316.902	1316.377	1470.286	1316.30
Multl-3	490.0	375.767	364.0	373.787	452.166	375.75	451.509	364.0
Bilatl-1	81.0	56.358	8.0	55.908	56.443	72.785	55.996	8.0
Firm	500.0	500.0	500.0	500.0	500.0	500.0	500.0	500.0
Total Trnas.	6059.6	5468.011	5234.16	5614.112	5545.094	5484.344	5692.116	5407.81
Total losses	195.364	174.400	172.988	178.228	173.256	174.430	177.058	174.644

Table 2.7.1: Desired Value of Multilateral Transaction-1
(UPSEB-75 bus system), Pattern-2

S. No.	Generators bus no.	Generation (MW)	S. No.	Load bus no.	Load (MW)
1.	1	401.32	1	20	156.37
2.	2	260.0	2	25	210.48
3.	3	180.0	3	27	306.00
4.	9	550.0	4	37	144.28
5.	11	109.0	5	42	1000.0
6.	12	1800.0	6	46	156.34
			7	47	74.55
			8	48	50.83
			9	49	85.72
			10	50	202.10
			11	51	57.76
			12	52	98.27
			13	60	74.20
			14	64	56.79
			15	66	31.74
			16	67	96.43
			17	68	42.87
			18	70	23.34
			19	71	91.73
			20	72	52.52
			21	74	288.00
Total		3300.32	Total		3300.32

Table 2.7.2: Desired Value of Bilateral Transaction-2
(UPSEB-75 bus system), Pattern- 2

S. No.	Generator bus no.	Generation (MW)	S. No.	Load bus no.	Load (MW)
1	1	140.28	1	56	140.28

Table 2.8.1: Results of OPD of Multilateral Transaction-1
(UPSEB-75 bus system), Pattern-2

Bus number	Constrained generation & load (MW)				
	Case-3(a)	Case-3(b)	Case-3(c)	Case-3(d)	Case-3(c)
Generations					
1	**206.832**	**197.723**	**198.828**	**210.101**	**206.121**
2	**260.0**	**260.0**	**260.0**	**260.0**	**260.0**
3	**180.0**	**180.0**	**180.0**	**180.0**	**180.0**
9	**550.0**	**550.0**	**550.0**	**550.0**	**550.0**
11	**109.0**	**109.0**	**109.0**	**109.0**	**109.0**
12	**1800.0**	**1800.0**	**1800.0**	**1800.0**	**1800.0**
Loads					
20	147.155	146.724	146.776	147.310	147.121
25	198.076	197.496	197.556	198.285	198.031
27	287.967	287.123	287.225	288.271	287.901
37	135.778	135.379	135.428	135.920	135.746
42	941.070	938.310	938.644	942.061	940.854
46	147.127	146.695	146.748	147.282	147.093
47	70.157	69.951	69.976	70.231	70.141
48	47.835	47.694	47.711	47.885	47.824
49	80.669	80.432	80.461	80.753	80.650
50	190.190	189.632	189.700	190.390	190.147
51	54.356	54.356	54.216	54.413	54.344
52	92.479	92.208	92.241	92.576	92.458
60	69.827	69.623	69.647	69.901	69.811
64	53.443	53.287	53.306	53.500	53.431
66	29.870	29.782	29.793	29.901	29.863
67	90.747	90.481	90.513	90.843	90.727
68	40.344	40.225	40.240	40.386	40.334
70	21.965	21.900	21.908	21.988	21.960
71	86.324	86.071	86 102	86.415	86.305
72	49.425	49.280	49.298	49.477	49.414
74	271.028	270.233	270.329	271.313	270.966
Total transaction (Gen. 1+2+3+9+11 +12)	3105.832	3096.723	3097.828	3109.101	3105.121

Table 2.8.2: Results of OPD of Multilateral Transaction-2
(UPSEB-75 bus system), Pattern-2

Bus number	Constrained generation & load (MW)				
	Case-3(a)	Case-3(b)	Case-3(c)	Case-3(d)	Case-3(e)
Generations					
4	**107.0**	**107.0**	**107.0**	**107.0**	**107.0**
10	**87.0**	**87.0**	**87.0**	**87.0**	**87.0**
13	**900.0**	**900.0**	**900.0**	**900.0**	**900.0**
15	**251.163**	**241.279**	**242.472**	**45.0**	**45.0**
Loads					
24	191.173	189.768	189.938	161.873	161.873
28	104.276	103 510	103.602	88 295	88.295
54	139.035	138.013	138.137	117.726	117.726
55	234.621	232.898	233.106	198.663	198.663
61	91.242	90.571	90 652	77.258	77.258
63	50.401	50.030	50.075	42.676	42.676
65	126.000	125.075	125.186	106.689	106.689
73	408.415	405.414	405.776	345.820	345.820
Total transaction (Gen. 4+10+13+15)	1345.163	1335.279	1336.472	1139.0	1139.0

Table 2.8.3: Results of OPD of Multilateral Transaction-3
(UPSEB-75 bus system), Pattern-2

Bus number	Constrained generation & load (MW)				
	Case-3(a)	Case-3(b)	Case-3(c)	Case-3(d)	Case-3(e)
Generations					
5	**180.0**	**180.0**	**180.0**	**180.0**	**180.0**
6	**110.0**	**110.0**	**110.0**	**110.0**	**110.0**
7	**60.0**	**60.0**	**60.0**	**60.0**	**60.0**
14	**40.376**	**35.277**	**35.870**	**14.0**	**14.0**
Loads					
30	180.521	178.163	178.437	168.324	168.324
32	62.229	61.416	61.511	58.025	58.025
39	67.814	66.929	67.031	63.232	63.232
62	79.812	78.769	78.891	74.419	74.419
Total transaction (Gen. 5+6+7+14)	390.376	385.277	385.870	364.0	364.0

Table 2.8.4: Results of OPD of Bilateral Transaction-1
(UPSEB-75 bus system), Pattern-2

Bus number	Constrained generation & load (MW)				
	Case-3(a)	Case-3(b)	Case-3(c)	Case-3(d)	Case-3(e)
Gen. 8	**59.421**	**58.362**	**73.496**	**16.832**	**15.433**
Load 34	59.421	58.362	73.496	16.832	15.433

Table 2.8.5: Results of OPD of Bilateral Transaction-2
(UPSEB-75 bus system), Pattern-2

Bus number	Constrained generation & load (MW)				
	Case-3(a)	Case-3(b)	Case-3(c)	Case-3(d)	Case-3(e)
Gen. 1	**14.0**	**72.414**	**72.782**	**14.0**	**42.680**
Load 56	14.0	72.414	72.782	14.0	42.680

Table 2.8.6: Summary of Optimal Power Dispatch Results
(UPSEB-75 bus system), Pattern-2

Transaction	Desired value(MW)	Constrained value (MW)				
		Case-3(a)	Case-3(b)	Case-3(c)	Case-3(d)	Case-3(e)
Multl-1	3300.32	3105.832	3096.723	3097.828	3109.101	3105.121
Multl-2	1548.0	1345.163	1335.279	1336.472	1139.0	1139.0
Multl-3	490.0	390.376	385.277	385.870	364.0	364.0
Bilatl-1	81.0	59.421	58.362	73.496	16.832	15.433
Bilatl-2	140.28	14.0	72.414	72.782	14.0	42.680
Firm	500.0	500.0	500.0	500.0	500.0	500.0
Total Trans.	6059.6	5414.792	5448.055	5466.448	5142.933	5166.234
Total losses	195.364	159.399	166.416	166.525	158.284	161.54

Table 2.9: Desired Value of Multilateral Transaction-1
(UPSEB-75 bus system), Pattern-3

S. No.	Generators bus no.	Generation (MW)	S. No.	Load bus no.	Load (MW)
1.	1	529.6	1	20	156.37
2.	2	260.0	2	25	210.48
3.	3	180.0	3	27	306.00
4.	9	550.0	4	37	144.28
5.	11	109.0	5	42	1000.0
6.	12	1800.0	6	46	156.34
			7	47	74.55
			8	48	50.83
			9	49	85.72
			10	50	202.10
			11	51	57.76
			12	52	86.27
			13	56	140.28
			14	60	74.20
			15	64	56.79
			16	66	31.74
			17	67	96.43
			18	68	42.87
			19	70	23.34
			20	71	91.73
			21	72	52.52
			22	74	288.00
Total		3428.60	Total		3428.60

Table 2.10.1: Results of OPD of Multilateral Transaction-1 (UPSEB-75 bus system), Pattern-3

Bus number	Constrained generation & load (MW) Case-4
Generations	
1	**521.710**
2	**260.0**
3	**180.0**
9	**550.0**
11	**109.0**
12	**1800.0**
Loads	
20	156.01
25	209.996
27	305.296
37	143.948
42	997.700
46	155.98
47	74.378
48	50.713
49	85.523
50	201.635
51	57.627
52	86.072
56	139.957
60	74.029
64	56.659
66	31.667
67	96.208
68	42.771
70	23.286
71	91.519
72	52.339
74	287.337
Total transaction (Gen. 1+2+3+9+11+12)	3420.710

Table 2.10.2: Results of OPD of Multilateral Transaction-2 (UPSEB-75 bus system), Pattern-3

Bus number	Constrained generation & load (MW) Case-4
Generations	
4	**107.0**
10	**87.0**
13	**900.0**
15	**410.829**
Loads	
24	213.865
28	116.653
54	155.538
55	262.470
61	102.072
63	56.382
65	140.956
73	456.893
Total transaction (Gen. 4+10+13+15)	1504.829

Table 2.10.3: Results of OPD of Multilateral Transaction-3 (UPSEB-75 bus system), Pattern-3

Bus number	Constrained generation & load (MW) Case-4
Generations	
5	**180.0**
6	**110.0**
7	**59.845**
14	**140.0**
Loads	
30	226.518
32	78.085
39	85.094
62	100.148
Total transaction (Gen. 5+6+7+14)	489.845

Table 2.10.4: Results of OPD of Bilateral Transaction-1
(UPSEB-75 bus system), Pattern-3

Bus number	Constrained generation & load (MW) Case-4
Gen. 8	**81.0**
Load 34	81.0

Table 2.10.5: Summary of Optimal Power Dispatch Results
(UPSEB-75 bus system), Pattern-3

Transactions	Desired value (MW)	Constrained value (MW) Case-4
Multl-1	3428.6	3420.71
Multl-2	1548.0	1504.829
Multl-3	490.0	489.845
Bilatl-1	81.0	81.000
Firm	500.0	500.000
Total Transaction	6047.6	5996.384
Total losses	192.760	190.043

2.5 Conclusions

This chapter has presented an optimal power dispatch model for congestion management and minimization of the load curtailment. The proposed method is quite simple to be adopted for optimal power dispatch in deregulated market. Presence of bilateral, multilateral and firm transactions have been considered. The studies have been conducted on IEEE-14 bus and UPSEB-75 bus system From the results presented in this chapter, following main conclusions can be made.

1. Higher premium price of willingness to pay to a group lower the curtailment in the desired transaction of that particular group. Higher premium price of willingness to pay to a bigger group makes slight improvement in that transaction but causes severe curtailment to the other smaller powers transaction groups resulting in lowering the total power transaction and vice-versa.
2. Higher premium price of willingness to pay simultaneously by two transactions benefits the bigger transaction group but hardly cause any benefit to the smaller power transaction group. This also causes severe curtailment to the remaining groups.
3. If any load, out of the multilateral transaction group, forms a separate bilateral group, this load suffers very badly but benefits the other bilateral/multilateral transaction groups even though the premium price of willingness to pay remains the same.
4. Congestion in a line connected in radial feeder may cause severe curtailment in the total power transaction. So, it is recommended that in congested case of the radial line, the desired load at its end may be suitably reduced at the time of entering in to the transaction.

Chapter 3

Impact of FACTS Devices on Congestion Management and Loss Allocation

3.1 Introduction

In an electricity market, generally, the market participants do not directly trade for the system losses caused by the anticipated transactions between them. However, anyone taking part in the electricity trading pay some kind of fee for the transmission access, which also includes charges for supply of losses. In a deregulated market, losses can be compensated in many different ways, which generally depend on the structure of the primary electricity market in place. In a competitive environment, one could consider at least three qualitative different ways of compensating for the losses,

1. Each market participant produces locally the power necessary to compensate for the losses
2. A market participant pays an additional charge for the real power loss compensation to some other market participant who compensates line loss in a bilateral basis.
3. The most discussed option is to have an ISO produce additional generation and compensate for total transmission loss and charge the users responsible for creating losses appropriately.

Out of the above, the third approach is usually applied for which an optimal power dispatch (OPD) model has been described in this chapter. Total transmission losses caused by all the trades on a network can either be measured or calculated, but the allocation of losses to individual trade is non-trivial. It is argued that due to non-linear nature of the loss relationship, it is difficult to allocate losses to individual trades in a theoretically correct manner. If the transmission loss were a linear function of the

generation, the allocation would be easier. Linear approximation of the losses has been used in [11], which always provides overestimate. In [26] the loss allocation approach for only bilateral transaction based on loss sensitivity has been suggested. In this chapter, loss allocation strategies both for the bilateral and multilateral transaction have been developed. The total real power transmission loss have been expressed using a general loss formula given in [29].

At present, a great deal of interests lie in determining the role that flexible AC transmission system (FACTS) equipment might play in the emerging competitive utility business environment. In recent past, FACTS application [16] have been considered in the power system to maximize the use of the existing transmission facilities and to enhance stability limit. The FACTS-based transmission capacity enhancement is seen as an environmentally and economically sound alternative to the new transmission line based augmentation of the capacity. In this chapter, the role of flexible AC transmission system devices on reducing the transmission congestion and curtailment of the contracted power has been studied. Two types of the FACTS devices, namely static VAR compensator (SVC) and thyristor controlled series compensator (TCSC), have been included in the optimal power dispatch model. The studies have been carried out on the modified IEEE-14 bus and UPSEB-75 bus systems.

3.2 Transmission Loss Allocation Model

As discussed in the previous chapter, ISO makes transaction with some GENCO to compensate for transmission losses. For the sake of simplicity, in this work, it is assumed that all the losses in both the systems i.e. IEEE-14 bus system and UPSEB-75 bus system are purchased by the ISO from generator at bus-1. To distribute the losses appropriately among the individual trades requires that the exact amount of the loss caused by each trade is accurately known. This task becomes difficult if the transmission losses caused by a trade depend on the other trades also. After knowing the amount of the loss caused by each trade, the cost of the same can be allocated to them.

The general mathematical formulation given in [26] for loss allocation to the bilateral transactions has been extended, in this work, to the multilateral contracts also. Transmission loss sensitivity with respect to the nodal real power has been derived using a general loss formula [29] as following:

3.2.1 Bilateral Contracts

Using the general loss formula, total system real power transmission loss (P_L) can be expressed as

$$P_L = \sum_{i=1}^{N}\sum_{j=1}^{N}[\alpha_{ij}(P_iP_j + Q_iQ_j) + \beta_{ij}(Q_iP_j - P_iQ_j)] \qquad \text{....(3.1)}$$

Where P_i = injected real power at bus i

Q_i = injected reactive power at bus i

α_{ij} and β_{ij} are the loss coefficients, given as

$$\alpha_{ij} = \frac{r_{ij}}{V_iV_j}\cos(\delta_i - \delta_j) \qquad \text{.........(3.2)}$$

$$\beta_{ij} = \frac{r_{ij}}{V_iV_j}\sin(\delta_i - \delta_j) \qquad \text{........(3.3)}$$

where, r_{ij} = Real part of the ijth element of [Z-bus]

V_i, V_j = Magnitude of bus voltages at ith & jth,bus, respectively

δ_i, δ_j = Voltage angles at ith & jth, bus, respectively

N = Number of buses

The key relation in the loss allocation analysis is the incremental power balance equation which takes the form of

$$\sum_{i=1}^{N}\gamma_i dP_i = 0 \qquad \text{.......(3.4)}$$

Where, dP_i is the deviation in net power injection at bus i and γ_i is the parameter which has to be worked out.

It is also known that

$$\sum_{i=1}^{N} dP_i = dP_L \qquad \text{.........(3.5)}$$

Let the bus 's' be the slack bus. From the standard load flow sensitivity analysis, dP_L can be expressed in terms of (N-1) incremental injections, excluding the slack bus incremental injection dPs, thus

$$\sum_{\substack{i=1 \\ \neq s}}^{N} \left(\frac{\partial P_L}{\partial P_i}\right) dP_i = dP_L \qquad \text{.........(3.6)}$$

where, Incremental transmission loss $\dfrac{\partial P_L}{\partial P_i}$ can be derived from equation (3.1) as,

$$\frac{\partial P_L}{\partial P_i} = 2.\sum_{j=1}^{N} (\alpha_{ij} P_j - \beta_{ij} Q_j) \quad \text{i} = 1, \ldots, \text{N} \qquad \text{............(3.7)}$$

From the equations (3.5) and (3.6) above

$$\sum_{\substack{i=1 \\ \neq s}}^{N} \left(1 - \frac{\partial P_L}{\partial P_i}\right) dP_i = 0 \qquad \text{...........(3.8)}$$

From equations (3.4) & (3.8), a possible set of values for γ_i is

$$\gamma_i = 1 - \frac{\partial P_L}{\partial P_i} \qquad \text{............(3.9)}$$

When a contract between generator j and load k varies by dPB_{jk}, the injection into the load bus k must vary by

$$dP_k = -dPB_{jk} \qquad \text{.....(3.10)}$$

While that at the generating bus, it changes by,

$$dP_j = dL_{jk} + dPB_{jk} \qquad \text{.......(3.11)}$$

Where, dL_{jk} is the incremental loss created by the transfer of power from bus j to bus k. However, the buyer at bus 'k' need not necessarily buy its losses from the bus 'j'. It is supposed that the incremental losses associated with an incremental transaction dP_{jk} can be purchased at an arbitrary bus 's', thus by superposition taking one contract increment at a time (consider an increment in contract jk, by dP_{jk}), from equation (3.4)

$$\gamma_j dP_j + \gamma_k dP_k + \gamma_s dP_s = 0 \qquad \text{..(3.12)}$$

where dP_k and dP_j are given by equations (3.10) and (3.11), while the associated incremental losses are bought from bus 's'.

$$dP_s = dL_{jk} \qquad ..(3.13)$$

From equations (3.10), (3.11), (3.12), & (3.13) the following incremental loss allocation is obtained.

$$dL_{jk} = (\frac{\gamma_k - \gamma_j}{\gamma_s})dPB_{jk} \qquad ....(3.14)$$

From equations (3.14) we can compute dL_{jk} matrix. The total loss are to be purchased from bus-1, (slack bus s =1). In order to allocate the total losses, it is assumed that PB_{jk} varies linearly with respect to some scalar 't' i. e.

$$dPB_{jk}(t) = dPB_{jk}.t \qquad ....(3.15)$$

From equations (3.14) & (3.15), we get

$$\frac{dL_{jk}(t)}{dt} = \frac{\gamma_k - \gamma_j}{\gamma_1}dPB_{jk} \qquad ....(3.16)$$

Integrating the above equation (3.16) from t=0 to t=1, using trapezoidal rule, we get

$$L_{jk} = 0.5(\frac{\gamma_k - \gamma_j}{\gamma_1})PB_{jk} \qquad ....(3.17)$$

We also know that

$$\sum_{j=1}^{N}\sum_{k=1}^{N} L_{jk} = P_L \qquad ....(3.18)$$

In practice, PB_{jk} may not vary linearly with some scalar 't' and hence eq. (3.18) may not exactly match if L_{jk} is computed from eq. (3.17). However terms described in eq.(3.17) can be used to determine the share of each transactions to losses. The total losses P_L can be allocated in the following ratio.

$$L_{jk} \propto (\frac{\gamma_k - \gamma_j}{\gamma_1})PB_{jk} \qquad ....(3.19)$$

Using eqn. (3.18) and (3.19), the total losses in the bilateral contract can be allocated.

3.2.2 Multilateral Contracts

Suppose, in a particular kth multilateral contract, a total power from N_g number of generator buses are taken to a total N_d number of load buses, in such a way, that

$$\sum_{i=1}^{N_g} PM_{ik} = \sum_{j=1}^{N_d} DM_{jk} \qquad \ldots(3.20)$$

where, PM_{ik} = Power generated for kth contract at ith bus

DM_{jk} = Power demand for kth contract at jth bus

k = 1...K (total number of multilateral contracts)

Each of the N_d power purchases (say jth) in each of the multilateral contracts (say kth) can be considered as N_g number of bilateral contracts (i =1,...N_g) such that

$$DB_{ji} = PB_{ij} = \frac{PM_{ik}}{\sum_{i=1}^{N_g} PM_{ik}} DM_{jk} \qquad \ldots.(3.21)$$

Advantage of the above assumption is that the loss can be computed in a similar way as derived for the bilateral contracts above. The total losses in a multilateral transaction shall be found out by adding the corresponding bilateral losses.

$$L_{jk} = \sum_{i=1}^{Ng} L_{ji} \quad ,\ j=1\ldots.Nd\ \ ,\ k=1\ldots K \qquad \ldots..(3.22)$$

3.3 FACTS Devices in OPD Modeling and Their Placement Criteria

Although there are several FACTS devices for controlling the real power flow in the system, for this study, only thyristor controlled series compensator (TCSC) and static VAR compensator (SVC) have been considered. Static model of FACTS devices has been utilized in the optimal power dispatch formulation, as given below.

a) *Thyristor controlled series compensator:* For steady state operation, the TCSC has been considered as a static capacitor/reactor offering impedance jXc. The transmission congestion can be relieved,

- By operating the TCSC in reactor mode and putting it in series with the congested line,

or

- By operating the TCSC in capacitor mode and suitably placing in series with a line other than the congested line. Accordingly, two alternative locations of TCSC has been considered in the system, one in the most congested line and the other in one of the remaining line found through hit and trial, which relieves the congestion maximum.

b) Static VAR compensator: In this formulation, the SVC has been considered as a reactive power source with the following limits.

$$Q_{ind} = B_{ind} V_{ref}^2 \qquad \text{.......(3.23)}$$

$$Q_{cap} = B_{cap} V_{ref}^2 \qquad \text{.........(3.24)}$$

where, B_{ind} = Inductive limiting value of susceptance of the SVC

B_{cap} = Capacitive limiting value of susceptance of the SVC

V_{ref} - Reference voltage magnitude

The optimal SVC location has been determined, through hit and trial, at one of the load buses where it is most effective in minimizing congestion and maximizing transaction.

3.4 Computational Steps

Computational steps for solving OPD considering the two types of FACTS devices (TCSC and SVC), considered in this study and for loss allocation are as following.

3.4.1 OPD with TCSC

The main steps involved are as following,

Step-1: a) If the TCSC is operated in reactive mode, replace series impedance of the line Z_{ser}^{old}, in which the TCSC is placed, by Z_{ser}^{new} given as under

$$Z_{ser}^{new} = Z_{ser}^{old} + jX_{cl} \qquad \text{..........(3.25)}$$

Where,

jX_{cl} = Static value of inductive reactance offered by the TCSC,

the TCSC is proposed to be placed in series with the most congested line in this case.

b) If the TCSC is operated in capacitive mode, replace series impedance of the line Z_{ser}^{old} of all the lines one by one by Z_{ser}^{new} given as under

$$Z_{ser}^{new} = Z_{ser}^{old} - jX_{c} \qquad \text{..........(3.26)}$$

Where,

jX_{c} = Static value of the capacitive reactance offered by the TCSC,

TCSC is placed in the lines other than the congested line in this case.

Step-2: Form [Y-bus] for each of the above cases with the new value of Z_{ser}^{new} of the lines.

Step-3: Run the load flow for each of the above cases with the desired transactions of real power.

Step-4: Check from the load flow solution, where the placement of TCSC is most effective in relieving the congestion of the transmission system. It will give the optimal placement of the TCSC and use this [Y-bus] for the future steps.

Step-5: Perform all the steps (step-2 to step-5) as given in chapter-2, section 2.3.4 to run the OPD with TCSC.

3.4.2 OPD with SVC

This involves following main steps,

Step-1: Read the system data and form [Y-bus] matrix for the base case.

Step-2: Placement of SVC has been considered at the load buses only. In this work, SVC at a load bus has been modeled similar to a synchronous condenser with pre specified reactive power limits.

Step-3: Run a load flow for each of the SVC locations with the desired transactions of the real power.

Step-4: Consider the optimal location of the SVC at a load bus that gives the maximum relief in congestion of the transmission line.

Step-5: Go through all the steps (step-2 to step-5) as given in chapter-2, section 2.3.4 to run the OPD with SVC.

3.4.3 Loss Allocation

The loss allocation model given in section 3.2 above is very simple and non-iterative. After running the OPD with or without FACTS devices, the following computational steps have been followed for computing the loss allocation.

Step-1: Compute bus voltages V_i, [Z-bus] matrix and total system losses (P_L) under the final curtailed/uncurtailed transaction dispatch.

Step-2: Compute α and β loss coefficients given by equations (3.2) and (3.3).

Step-3: Compute $\frac{\partial P_L}{\partial P_i}$ given by equation (3.7).

Step-4: Compute γ_i given by equation (3.9).

Step-5: Allocate the loss to each bilateral transaction in the ratio as given by equation (3.19) and to the multilateral transactions as per the equation (3.20) to (3.22).

3.5 Study Results

The studies have been conducted on the IEEE-14 system and the UPSEB-75 bus system. The system data are given in Appendix-A and B, respectively. The system losses are assumed to be supplied by the generator at bus-1 only under a system regulation transaction between ISO and the seller at the generator bus-1. The base case operating condition of both the systems are given in Appendix-A and B. Detailed results of the studies conducted on these two systems are given in following sections.

3.5.1 IEEE-14 bus test system

3.5.1.1 Impact of the FACTS Devices

The line ratings in terms of square of the current (I^2 p. u.) of the IEEE-14 bus system are given in table 3.1. Two groups of multilateral contracts, same as in chapter-2, were considered. The details of desired generation and loads of in the IEEE-14 bus system with the two multilateral transactions are same as given in table 2.1 of chapter 2. As it is already seen in chapter 2 that, if the desired power transaction are dispatched without placing any FACTS device, the line-10 between bus 4 and 11 become overloaded. The loading pattern of the line under this condition is reproduced in table 3.1. In this chapter, the optimal power dispatch study has been conducted with FACTS devices. The two case studies include case-1 with one TCSC placed in the system and case-2 with one SVC considered in the system. The TCSC has been placed first on the most congested line (line-10 in this case) and its operation considered in inductive mode. The most effective setting was found at compensation of 62.7%, which eliminates the congestion completely. Alternatively, it was placed in all other lines, one by one, in capacitive mode and the most effective placement was found in line-20 with a compensation of 80%.

The SVC placement was decided by hit and trail method considered at each load bus. The best placement was found at bus-10 with a setting of 50 MVAR capacitive. Results of these three case studies are given in tables 3.2 and 3.3, which are described below.

Case-1, OPD with TCSC: When a TCSC, operated in inductive mode, is placed in series with the congested line-10 connected between buses 4 and 11, with an inductive reactance of 62.7% of the line reactance, the congestion of the line gets completely eliminated. This case is referred as case 1(a) in table-3.2. In capacitive mode of operation of TCSC, located in line-20 with a capacitive reactance of 80%, it is found that the line-10 is still overloaded if the desired power transactions are to be dispatched, as shown in table-3.1 (line loading is 0.2934 p.u. as against rating of 0.25 p.u.). However, the congestion on line-10 has reduced from 0.3222 p.u.(without FACTS) to 0.2934 p.u.(with TCSC). Even after putting the TCSC, ISO has to curtail the initial power transfers in order to keep the operating system within security limits. Curtailment strategy with TCSC are referred as case 1(b) to case 1(g) which are similar to cases 1(a) to 1(f), respectively, as given in chapter-2, section 2.4.1

In table-3.2 the optimal dispatch results for cases 1(b) to 1(g) show that the total power transaction and individual power transactions are increased to a large extent when compared to cases 1(a) to 1(f) of chapter-2, section 2.4.1 (OPD without FACTS devices), respectively. The curtailment in the transactions desired by the market participants is also considerably reduced.

Case-2, OPD with SVC: The placement of SVC was considered at bus-10 with bus voltage as 1.08 p. u. and reactive power limits as ±50 MVAR. From the results given in table-3.1, it is found that the line-10 is overloaded, if the desired power transactions are dispatched. The transmission line-10 gets overloaded to 0.2940 p. u. against its rating of 0.25 p. u. even with placement of SVC. However, it has been reduced from the base case flow (without FACTS devices) of 0.3222 p.u.. Hence, even after placing the SVC, ISO has to curtail the initial power transfers in order to keep operating system within security limits. Curtailment strategy with SVC is referred as 2(a) to 2(f) which are similar to cases 1(a) to 1(f) given in chapter-2, section 2.4.1 (OPD without FACTS devices), respectively.

From the results presented in table-3.3, it is observed that the total power transaction and individual power transactions have increased to a large extent, which are even more than the case-1 with TCSC. The curtailment in the desired transactions is considerably reduced.

3.5.1.2 Loss Allocation

Loss allocation were computed for all the cases 1(a) to 1(f) of section 2.4.1 in chapter-2 (i.e. OPD without FACTS devices and cases) 1(a) to 1(g) & 2(a) to 2(f) described in this chapter section 3.5.1.1 using the approach explained in section 3.2 and 3.4.3. However, table 3.5, 3.6 and 3.7 show the results of few typical cases only, namely 1(a) of chapter 2 (OPD without FACTS devices), case-1 (b) of this chapter (OPD with TCSC) and case-2 (a) of this chapter (OPD with SVC).

3.5.2 UPSEB-75 Bus Test System

3.5.2.1 Impact of the FACTS Devices

The line ratings in terms of square of the current (I^2 p. u.) of the UPSEB-75 bus system are shown in table 3.1. Three groups of multilateral contracts, one group of bilateral contract and a firm power transaction, exactly same as pattern-1 given in section 2.4.2.1 of chapter 2, have been considered in this work. The details of desired generation and loads of the UPSEB-75 system, for pattern-1, are shown in table 2.4 of chapter 2. As it is already seen in chapter 2, that if the desired power transactions are dispatched without placing any FACTS devices, the lines 4, 36 and 89 get overloaded. The loading pattern of the lines under this condition is reproduced in table 3.8.

The two case studies of optimal power dispatch with FACTS devices include case-3 with one TCSC placed in the system and case-4 with one SVC considered in the system. Results obtained for these cases are described below –

Case-3, OPD with TCSC: The TCSC in inductive mode was placed first on the most congested line (line-36 in the case) and it was found that it gave no relief to the congestion of the network in the system. Alternatively, it was placed in all the lines,

one by one, in capacitive mode and it is seen that it also gives no relief to the congestion of line-36 at any setting of the TCSC. Then, the placement of TCSC, in this case, is not at all helpful in relieving the congestion, as the line-36 is a part of a radial feeder in the 75-bus UPSEB system.

The loading at the bus no.-52, which is located at the end of line-36 was reduced by 12 MW so that the congestion of line-36 is eliminated without placement of any FACTS device. Hence, the new loading pattern was exactly similar to the pattern-3 given in clause 2.4.2.3 of chapter 2. It has been already discussed in chapter 2, that, in case of pattern –3 if all the desired loads are dispatched, the line no.4 & 89 still remain overloaded. The line flows under this condition are reproduced in table 3.8. The placement of TCSC was first tried on congested lines 4 & 89, one by one, in the inductive mode. It was found that it relieves congestion on line 4 or 89 but keeps the system still congested by making the other lines overloaded. So the placement of one TCSC in UPSEB system in inductive mode does not help in eliminating the overloading. Next the placement of TCSC was considered in all the lines, one by one, in capacitive mode and it was found to be most effective in line-29 with a setting of 54.8 % of the line inductive reactance. It eliminates the congestion completely. In this situation the ISO need not take curtailment action. The line loading conditions under this case, is shown in table 3.8.

Case-4, OPD with SVC: The SVC placement was decided by trial method and was considered at each load bus. The best placement was found at bus-27 with a setting of 250 MVAR capacitive and a bus voltage of 1.05 p. u. From the results given in table 3.8, it is found that even with the placement of the SVC as above, if all the desired transaction as per pattern –1 (described in chapter-2) are dispatched, the lines-36 and 89 remain overloaded though the congestion on line-4 is relieved. The loading of line-36 under this condition is 2.372 p. u. against its rating of 2.25 p. u. and that of line – 84 is 9.846 p. u. against its rating of 9.0 p. u. However, these have been reduced from their base case flows of 2.643 p. u. and 10.1958 p. u. respectively, without FACTS devices. Hence even after placement of the SVC, ISO has to curtail the initial power transfers in order to keep operating system within security limits. Curtailment strategy with SVC is referred as cases 4(a) to 4(g), which are similar to cases 2(a) to 2(g), respectively given in chapter 2. From the results presented in tables 3.9.1 to 3.9.5, it is observed that the total power transaction and individual power transactions have

increased to a large extent. The curtailment in the desired transaction is considerably reduced.

The total transactions with and without SVC for pattern-1 are also shown through bar chart as given in fig. 3.2 and in table 3.10.

3.5.2.2 Loss Allocation

Loss allocation for all the cases i.e. cases 2, 3 and 4 of chapter 2 (OPD without FACTS devices) and cases 3 and 4 of this chapter were computed using the approach explained in section 3.2 and 3.4.3 above. However tables 3.11.1 to 3.11.6 show the results of a typical case 2(a) given in chapter 2.

Table 3.1: Effect of Desired Transaction Dispatch on Line Flow

(IEEE-14 bus test system)

Line no.	Starting bus	End bus	Line rating (I^2) p. u.	Line Loading I^2 in (p. u.)			
				Without FACTS devices	With TCSC operated in inductive mode placed in line 10	With TCSC operated in capacitive mode placed in line 20	With SVC placed at bus 10
1	4	6	0.4225	0.1653	0.1319	0.1725	0.1377
2	7	8	0.4225	0.2990	0.3153	0.2662	0.3485
3	7	9	0.1600	0.0854	0.0899	0.0739	0.1008
4	1	2	2.9241	0.1502	0.1531	0.1470	0.1509
5	1	7	2.9241	0.4956	0.0501	0.4972	0.4734
6	2	3	2.9241	0.9797	0.0987	0.9743	0.9809
7	2	6	2.9241	1.0366	1.0267	1.0460	1.1084
8	2	7	2.9241	1.0753	1.0867	1.0695	1.0670
9	3	6	2.9241	1.1080	1.1012	1.1142	1.0987
10	**4**	**11**	**0.2500**	**0.3222**	**0.2500**	**0.2933**	**0.2940**
11	4	12	0.2500	0.0370	0.0388	0.0407	0.0341
12	4	13	0.2500	0.1895	0.2082	0.2312	0.1734
13	5	8	0.2500	0.0858	0.0916	0.0866	0.0276
14	6	7	2.9241	0.0525	0.0682	0.0451	0.0410
15	8	9	0.4225	0.2677	0.3022	0.2503	0.2499
16	9	10	0.2500	0.0295	0.0568	0.0366	0.0774
17	9	14	0.2500	0.0096	0.0087	0.0100	0.0216
18	10	11	0.2500	0.0016	0.0017	0.0006	0.0351
19	12	13	0.2500	0.0010	0.0013	0.0020	0.0010
20	13	14	0.2500	0.0374	0.0483	0.0639	0.0314

Table 3.2: Results of OPD with TCSC.

(IEEE-14 bus test system)

Bus no.	Desired generation & load(MW)	Constrained generation & load (MW)						
		Case-1(a)	Case-1(b)	Case-1(c)	Case-1(d)	Case-1(e)	Case-1(f)	Case-1(g)
1(loss- make up)	30.349	29.57	28.996	28.185	27.866	28.249	28.352	27.81
Group-1								
Gen-2	**157.7**	**157.7**	**157.7**	**157.7**	**153.232**	157.7	**157.7**	**157.7**
Gen-4	**98.0**	**98.0**	**84.922**	**85.064**	**87.185**	86.246	**84.246**	**86.688**
Load-7	102.9	102.9	97.637	97.694	96.75	98.17	97.566	96.461
Load-9	57.8	57.8	54.844	54.876	54.345	55.143	54.804	54.183
Load-11	53.5	53.5	50.764	50.793	50.302	51.041	50.727	51.152
Load-12	16.1	16.1	15.277	15.285	15.138	15.36	15.265	15.093
Load-14	25.4	25.4	24.101	24.115	23.882	24.232	24.083	23.811
Group-2								
Gen-3	**214.1**	**214.1**	**211.367**	**205.931**	**207.328**	206.73	**207.599**	**206.99**
Load-6	167.8	167.8	165.658	161.398	162.493	165.343	165.014	161.69
Load-10	19.0	19.0	18.757	18.275	18.399	16.543	18.071	19.0
Load-13	27.3	27.3	26.951	26.258	26.437	24.843	24.514	26.306
Total trans. Gen.2+3+4	469.8	469.8	453.987	448.695	447.745	450.673	450.044	446.691

Table3.3: Results of OPD with SVC

(IEEE-14 bus test system)

Bus no.	Desired generation & load(MW)	Constrained generation & load (MW)					
		Case-2(a)	Case-2(b)	Case-2(c)	Case-2(d)	Case-2(e)	Case-2(f)
1(loss make-up)	29.492	28.346	27.697	27.397	27.696	27.811	27.344
Group-1							
Gen-2	**157.7**	157.7	157.7	**153.992**	157.7	157.7	**153.764**
Gen-4	**98.0**	**85.71**	**85.689**	**87.304**	**86.473**	**85.307**	**86.889**
Load-7	102.9	97.954	97.946	97.045	98.261	97.792	96.845
Load-9	57.8	55.022	55.017	54.528	55.194	54.931	54.399
Load-11	53.5	50.929	50.924	50.472	51.088	50.844	50.352
Load-12	16.1	15.326	15.325	15.189	15.374	15.301	15.153
Load-14	25.4	24.179	24.177	23.962	24.255	24.139	23.905
Group-2							
Gen-3	**214.1**	**211.897**	**207.427**	**208.341**	**207.833**	**208.749**	**208.101**
Load-6	167.8	166.073	162.57	163.287	165.728	165.507	162.640
Load-10	19.0	18.805	18.408	18.489	16.928	18.236	19.0
Load-13	27.3	27.019	26.449	26.566	25.288	25.007	26.461
Total transaction Gen.2+3+4	469.8	455.307	450.816	449.567	452.056	451.756	448.754

Fig.3.1: Bar Chart showing Impact of the FACTS Devices on the Total Transaction

(IEEE-14 bus test system)

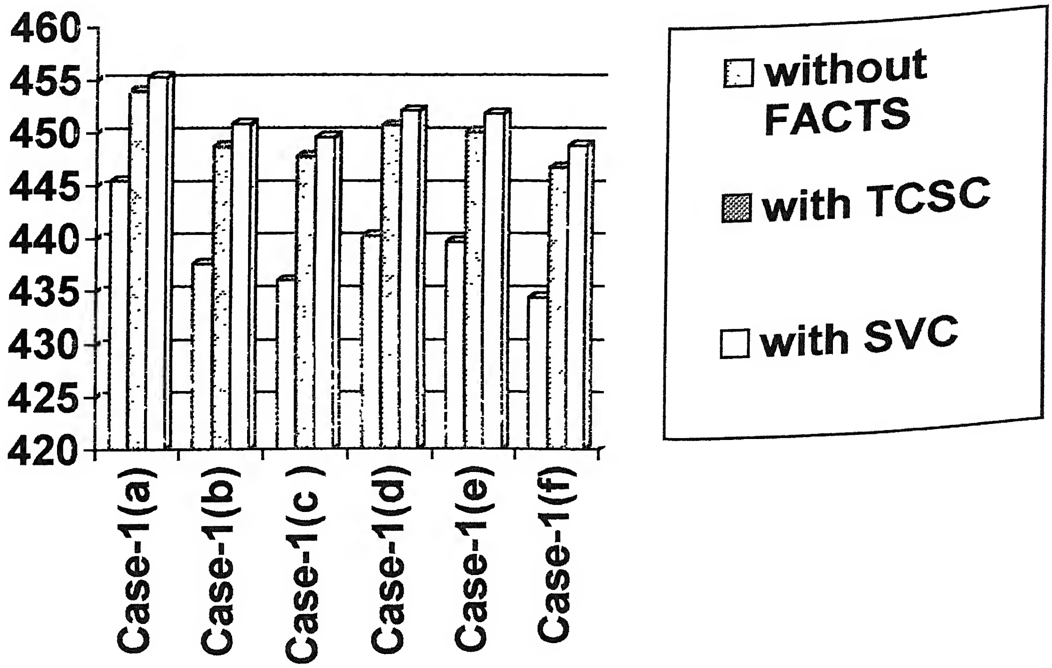


Table3.4: Impact of the FACTS Devices on the Total Transaction

(IEEE-14 bus test system)

Cases corresponding to case 1 of chapter 2	Total transaction (MW)		
	Without FACTS devices	With TCSC in capacitive mode	With SVC
Case-1(a)	445.460	453.987	455.307
Case-1(b)	437.582	448.695	450.816
Case-1(c)	435.986	447.745	449.567
Case-1(d)	440.256	450.673	452.056
Case-1(e)	439.635	450.044	451.756
Case-1(f)	434.362	446.691	448.754

Table3.5: Loss Allocation without FACTS Device Case-1 (a) [Chapter-2]

(IEEE-14 bus test system)

Load bus	Loss allocated to each transaction (MW)	Power transaction (MW)	Losses as % of the corresponding transaction	Transaction as % of total transaction	Loss allocated as % of total losses
Group-1					
7	4.1941	94.771	4.42546	21.27829	15.04047
9	2.9350	53.234	5.51332	11.95224	10.52515
11	3.4485	49.274	6.99869	11.06306	12.36681
12	0.6911	14.828	4.66103	3.32926	2.47853
14	1.7099	23.394	7.30944	5.25237	6.13204
Group-2					
6	11.0768	164.557	6.73367	36.93386	39.72305
10	1.7125	18 633	9.19424	4.18202	6.14141
13	2.1172	26.772	7.91090	6.00890	7.59254
Total	27 8851	445.462	6.25982	100	100

Table3.6: Loss Allocation with TCSC Case-1 (b) [Chapter-3].

(IEEE-14 bus test system)

Load bus	Loss allocated to each transaction (MW)	Power transaction (MW)	Losses as % of the corresponding transaction	Transaction as % of total transaction	Loss allocated as % of total losses
Group-1					
7	4.44266	97.637	4.55016	21.50652	15.33730
9	3.31292	54.844	6.04064	12.08043	11.43714
11	3.60059	50.764	7.09283	11.18172	12.43026
12	0.64492	15.277	4.22162	3.36497	2.22645
14	1.99594	24.101	8.28159	5.3087	6.89055
Group-2					
6	11.17047	165.658	6.74309	36.48939	38.56356
10	1.79077	18.757	9.54701	4.13169	6.18225
13	2.00809	26.951	7.45076	5.93659	6.93249
Total	28.96636	453.987	6.3804	100	100

Table3.7: Loss Allocation with SVC Case-2 (a) [Chapter-3].

(IEEE-14 bus test system)

Load bus	Loss allocated to each transaction (MW)	Power transaction (MW)	Losses as % of the corresponding transaction	Transaction as % of total transaction	Loss allocated as % of total losses
Group-1					
7	4.38410	97.954	4.47568	21.51387	15.46654
9	2.51653	55.022	4.57368	12.08457	8.87797
11	3.56494	50.929	6.99989	11.18554	12.57664
12	0.71684	15.326	4.67722	3.36612	2.52891
14	1.78472	24.179	7.38123	5.31052	6.29625
Group-2					
6	11.43741	166.073	6.88696	36.47505	40.34965
10	1.75316	18.805	9.32308	4.13007	6.18491
13	2.18805	27.019	8.09814	5.93426	7.71913
Total	28.34575	455.307	6.22563	100	100

Table 3.8: Effect of Desired Transaction Dispatch on Line Flow

(UPSEB-75 bus system), Patterns-1, & 3 [Chapter-2]

Line no.	Starting bus	End bus	Line rating (I^2) p. u.	Line loading I^2 in (p. u.)			
				Without FACTS devices when total transaction is 6059.6 MW(pattern 1)	Without FACTS devices when total transaction is 6047.6 MW(pattern 3)	With TCSC placed in line 29, total transaction is 6047.6 MW (pattern 3)	With SVC placed on bus-27, total transacti on is 6059.6 MW(pat tern 1)
1	19	20	23.040	7.734	7.723	7.661	7.645
2	17	16	23.040	6.459	6.275	6.117	6.169
3	22	25	23.040	12.687	12.663	12.500	12.396

4	**23**	**24**	**23.040**	**23.445**	**23.045**	**22.352**	**22.298**
5	26	27	23.040	14.810	14.281	14.137	15.246
6	29	30	51.840	41.570	41.483	40.641	40.628
7	36	37	23.040	3.101	3.105	3.095	3.078
8	38	39	5.760	1.098	1.097	1.074	1.090
9	45	44	39.690	2.271	2.298	1.708	2.561
10	16	2	22.278	6.668	6.642	6.605	6.477
11	18	3	23.040	3.630	3.615	3.707	3.013
12	17	1	92.160	51.349	49.304	47.836	50.489
13	28	4	3.422	1.150	1.145	1.128	1.096
14	31	5	7.618	2.992	2.990	2.981	2.960
15	32	6	1.538	1.114	1.113	1.110	1.105
16	33	7	1.000	0.334	0.333	0.329	0.327
17	34	8	6.250	1.035	1.033	1.067	0.972
18	35	9	51.840	29.039	28.968	28.888	28.531
19	24	10	6.250	0.798	0.782	0.758	0.796
20	40	11	14.063	1.482	1.463	1.439	1.299
21	41	12	564.538	297.703	297.555	297.359	295.935
22	42	13	138.298	74.513	74.478	74.431	74.089
23	43	14	27.878	2.051	2.035	1.989	1.885
24	44	15	43.560	20.226	20.231	16.622	20.334
25	16	46	9.000	4.574	4.452	4.513	4.473
26	16	50	20.250	13.094	12.839	12.643	12.623
27	17	19	25.000	15.414	15.082	14.791	15.246
28	17	23	25.000	8.583	8.307	8.172	8.326
29	23	29	25.000	10.806	10.749	10.399	10.329
30	20	64	2.250	0.344	0.343	0.340	0.335
31	19	26	30.250	7.769	7.409	7.166	7.964
32	47	50	9.000	2.804	2.706	2.672	2.834
33	47	67	9.000	0.919	0.897	0.867	0.852
34	24	27	9.000	0.460	0.362	0.369	1.014
35	24	54	9.000	8.359	8.369	8.301	8.126
36	**27**	**51**	**2.250**	**2.643**	**2.233**	**2.208**	**2.372**
37	51	52	2.250	1.056	0.810	0.801	0.944
38	25	60	2.250	0.556	0.555	0.549	0.539
39	25	43	2.250	0.014	0.012	0.009	0.000
40	34	54	9.000	0.010	0.010	0.020	0.005
41	54	28	9.000	1.259	1.257	1.130	1.167
42	28	43	3.240	0.051	0.050	0.043	0.037
43	28	56	9.000	0.631	0.634	0.623	0.648
44	56	30	9.000	0.014	0.013	0.015	0.025
45	30	57	3.240	2.062	2.059	2.064	2.026
46	53	30	3.240	0.689	0.689	0.666	0.674
47	53	61	2.250	0.002	0.002	0.001	0.000
48	30	61	2.250	0.157	0.157	0.147	0.152
49	57	58	3.240	0.001	0.001	0.000	0.000
50	57	59	3.240	0.008	0.007	0.006	0.005
51	59	39	2.250	1.525	1.522	1.506	1.483

52	39	32	2.250	0.178	0.178	0.184	0.180
53	39	33	9.000	0 359	0.358	0.351	0.338
54	54	63	2.250	0.077	0.080	0.101	0.115
55	55	63	3.240	0.248	0 246	0.162	0.251
56	61	62	2.250	0.407	0.406	0.393	0.393
57	62	32	9.000	2.615	2.611	2.576	2.565
58	31	32	12.960	2.994	2.991	2.983	2.960
59	35	36	25.000	10.264	10.099	9.944	10.085
60	46	37	2.250	0.228	0.226	0.223	0.235
61	19	36	25.000	2.749	2.666	2.603	2.808
62	17	35	36.000	4.967	5.047	5.115	4.839
63	20	40	9.000	0.119	0.114	0.105	0.088
64	40	48	2.250	0.630	0.629	0.625	0.622
65	74	41	25.000	14.364	14.346	14.384	14.005
66	74	41	25.000	17.768	17.746	17.792	17.324
67	74	73	25.000	11.670	11.639	12.418	11.094
68	26	22	25.000	13.262	13.210	12.896	12.416
69	29	22	30.250	0.206	0.204	0.210	0.196
70	26	41	25.000	22.928	22.882	22.780	22.891
71	48	49	2.250	0.085	0.085	0.084	0.084
72	49	40	2.250	0.495	0.494	0.491	0.488
73	38	29	30.250	0.565	0.563	0.553	0.540
74	38	22	30.250	0.350	0.345	0.330	0.278
75	18	47	12.960	0.186	0.201	0.240	0.244
76	30	65	12.960	1.223	1.221	1.148	1.195
77	41	42	36.000	21.634	21.618	21.472	21.251
78	42	74	25.000	13.605	13.588	13.627	13.250
79	20	66	2.250	0.115	0.114	0.113	0.112
80	23	74	144.000	27.216	27.212	26.236	26.476
81	24	67	12.960	0.010	0.008	0.003	0.023
82	18	68	3.240	0.847	0.824	0.824	0.685
83	18	71	2.890	0.522	0.504	0.503	0.465
84	27	68	2.890	0.196	0.186	0.186	0.209
85	27	71	3.250	0 046	0.049	0.050	0.108
86	25	72	2.250	0.581	0.580	0.574	0.564
87	43	58	2.250	0.910	0.909	0.902	0.896
88	43	56	9.000	0.267	0.265	0.253	0.245
89	**55**	**44**	**9.000**	**10.196**	**10.158**	**9.000**	**9.846**
90	73	45	100.000	1.601	1.611	1.052	1.689
91	29	75	36.000	18.662	18.625	18.526	18.154
92	37	69	9.000	0.433	0.432	0.430	0.423
93	70	72	3.240	0.055	0.055	0.054	0.053
94	21	65	12.250	0.118	0.117	0.110	0.115
95	21	30	2.250	0.114	0.113	0.106	0.110

Table 3.9.1: Results of OPD with SVC of Multilateral Transaction-1 (UPSEB-75 bus system), Pattern-1

Bus number	Constrained generation & load (MW)						
	Case-4(a)	Case-4(b)	Case-4(c)	Case-4(d)	Case-4(e)	Case-4(f)	Case-4(g)
Generations							
1	**452.267**	**452.506**	**452.325**	**452.353**	**452.370**	**452.300**	**452.351**
2	**260.0**	**260.0**	**260.0**	**260.0**	**260.0**	**260.0**	**260.0**
3	**180.0**	**180.0**	**180.0**	**180.0**	**180.0**	**180.0**	**180.0**
9	**550.0**	**550.0**	**550.0**	**550.0**	**550.0**	**550.0**	**550.0**
11	**109.0**	**109.0**	**109.0**	**109.0**	**109.0**	**109.0**	**109.0**
12	**1800.0**	**1800.0**	**1800.0**	**1800.0**	**1800.0**	**1800.0**	**1800.0**
Loads							
20	152.31	152.321	152.313	152.314	152.314	152.312	152.313
25	205.015	205.030	205.019	205.02	205.021	205.017	205.02
27	298.055	298.076	298.06	298.062	298.063	298.058	298.062
37	140.534	140.544	140.536	140.537	140.538	140.535	140.537
42	974.036	974.105	974.053	974.059	974.064	974.047	974.058
46	152.281	152.292	152.283	152.284	152.285	152.280	152.284
47	72.614	72.619	72.616	72.616	72.616	72.615	72.616
48	49.51	49.514	49.511	49.511	49.512	49.511	49.511
49	83.494	83.5	83.496	83.496	83.497	83.495	83.496
50	196.853	196.867	196.856	196.857	196.858	196.855	196.857
51	56.26	56.264	56.261	56.262	56.262	56.261	56.262
52	95.719	95.725	95.72	95.721	95.721	95.720	95.721
56	136.638	136.647	136.64	136.641	136.642	136.639	136.641
60	72.273	72.279	72.275	72.275	72.276	72.274	72.275
64	55.316	55.319	55.316	55.317	55.317	55.316	55.317
66	30.916	30.918	30.916	30.917	30.917	30.916	30.917
67	93.926	93.933	93.928	93.928	93.929	93.927	93.928
68	41.757	41.760	41.758	41.758	41.758	41.757	41.758
70	22.734	22.736	22.734	22.735	22.735	22.734	22.735
71	89.348	89.355	89.35	89.350	89.351	89.349	89.350
72	51.156	51.160	51.157	51.158	51.158	51.157	51.158
74	280.522	280.542	280.527	280.529	280.530	280.525	280.529
Total transaction (Gen. 1+2+3+9+11+12)	3351.267	3351.506	3351.325	3351.353	3351.370	3351.300	3351.351

Table 3.9.2: Results of OPD with SVC of Multilateral Transaction-2 (UPSEB-75 bus system), Pattern-1

Bus number	Constrained generation & load (MW)						
	Case-4(a)	Case-4(b)	Case-4(c)	Case-4(d)	Case-4(e)	Case-4(f)	Case-4(g)
Generations							
4	**107.0**	**107.0**	**107.0**	**107.0**	**107.0**	**107.0**	**107.0**
10	**87.0**	**87.0**	**87.0**	**87.0**	**87.0**	**87.0**	**87.0**
13	**900.0**	**900.0**	**900.0**	**900.0**	**900.0**	**900.0**	**900.0**
15	**355.807**	**153.836**	**421.504**	**355.916**	**355.911**	**421.504**	**355.824**
Loads							
24	206.045	177.341	215.382	206.06	206.06	215.382	206.047
28	112.388	96.731	117.481	112.397	112.396	117.481	112.389
54	149.851	128.975	156.641	149.862	149.862	156.641	149.853
55	252.873	217.646	264.332	252.892	252.891	264.332	252.876
61	98.340	84.64	102.796	98.347	98.347	102.796	98.341
63	54.321	46.754	56.782	54.325	54.325	56.782	54.322
65	135.802	116.884	141.956	135.813	135.812	141.956	135.804
73	440.187	378.865	460.134	440.22	440.218	460.134	440.192
Total transaction (Gen. 4+10+13+15)	1449.807	1247.836	1515.504	1449.916	1449.911	1515.504	1449.824

Table 3.9.3: Results of OPD with SVC of Multilateral Transaction-3 (UPSEB-75 bus system), Pattern-1

Bus number	Constrained generation & load (MW)						
	Case-4(a)	Case-4(b)	Case-4(c)	Case-4(d)	Case-4(e)	Case-4(f)	Case-4(g)
Generations							
5	**180.0**	**180.0**	**180.0**	**180.0**	**180.0**	**180.0**	**180.0**
6	**110.0**	**110.0**	**110.0**	**110.0**	**110.0**	**110.0**	**110.0**
7	**60.0**	**60.0**	**60.0**	**60.0**	**60.0**	**60.0**	**60.0**
14	**89.56**	**14.0**	**89.47**	**123.245**	**89.612**	**123.197**	**14.0**
Loads							
30	203.265	168.324	203.224	218.843	203.289	218.820	168.324
32	70.07	58.025	70.055	75.439	70.078	75.431	58.025
39	76.358	63.232	76.342	82.209	76.367	82.201	63.232
62	89.867	74.419	89.849	96.754	89.878	96.745	74.419
Total transaction (Gen. 5+6+7+14)	439.56	364.0	439.47	473.245	439.612	473.197	364.0

Table 3.9.4: Results of OPD with SVC of Bilateral Transaction-1

(UPSEB-75 bus system), Pattern-1

Bus number	Constrained generation & load (MW)						
	Case-4(a)	Case-4(b)	Case-4(c)	Case-4(d)	Case-4(e)	Case-4(f)	Case-4(g
Gen. 8	**70.243**	**48.879**	**70.23**	**70.261**	**77.418**	**70.237**	**48.682**
Load 34	70.243	48.879	70.23	70.261	77.418	70.237	48.682

Table 3.9.5: Summary of OPD Results with SVC

(UPSEB-75 bus system), Pattern-1

Trans-actions	Desired value (MW)	Constrained value (MW)						
		Case-4(a)	Case-4(b)	Case-4(c)	Case-4(d)	Case-4(e)	Case-4(f)	Case-4(g
Multl-1	3440.6	3351.267	3351.506	3351.325	3351.353	3351.370	3351.300	3351.351
Multl-2	1548.0	1449.807	1247.836	1515.504	1449.916	1449.911	1515.504	1449.824
Multl-3	490.0	439.56	364.0	439.47	473.245	439.612	473.197	364.0
Bilatl-1	81.0	70.243	48.879	70.23	70.261	77.418	70.237	48.682
Firm	500.0	500.0	500.0	500.0	500.0	500.0	500.0	500.0
Total Trans.	6059.6	5810.877	5512.221	5876.528	5844.775	5818.311	5910.238	5713.857
Total losses	195.364	180.086	178.031	183.341	180.753	180.085	183.011	182.358

Fig.3.2: Bar Chart showing Impact of SVC on the Total Transaction

(UPSEB-75 bus system Pattern-1)

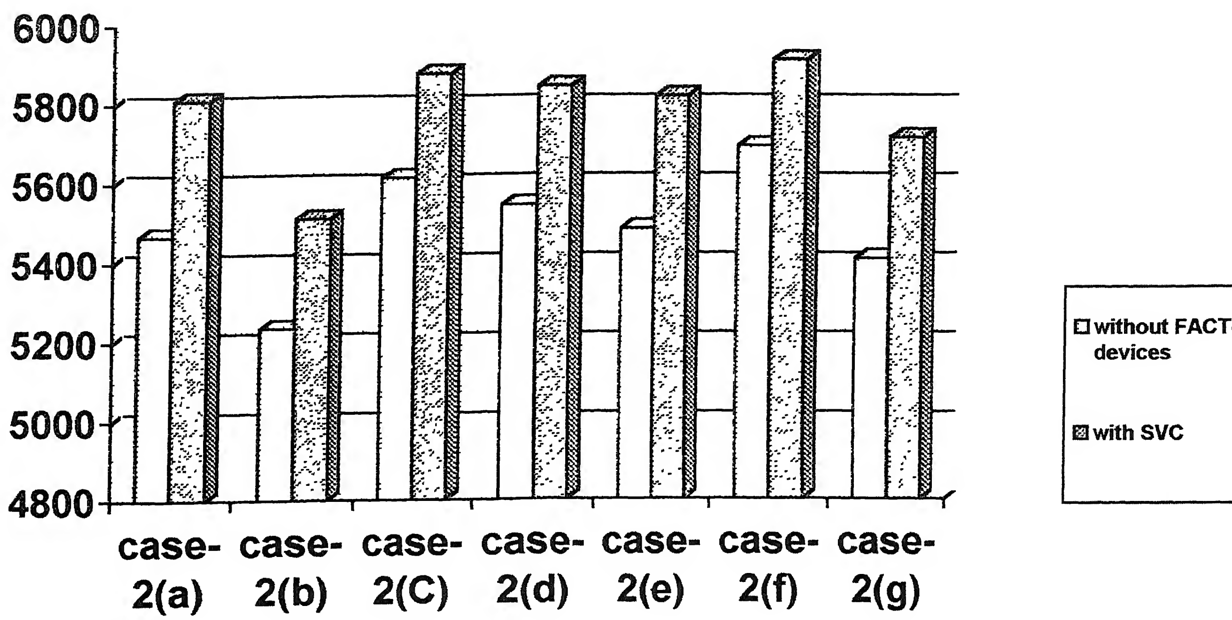


Table 3.10: Impact of SVC on the Total Transaction

(UPSEB-75 bus system, Pattern-1)

Case 2 of chapter 2	Total transaction (MW)	
	Without FACTS devices	With SVC
Case-2(a)	5468.011	5810.877
Case-2(b)	5234.160	5512.221
Case-2(c)	5614.112	5876.528
Case-2(d)	5545.094	5844.775
Case-2(e)	5484.344	5818.311
Case-2(f)	5692.116	5910.238
Case-2(g)	5407.819	5713.857

Table3.11.1: Loss Allocation without FACTS Device Case-2 (a) [Chapter-2].

(UPSEB-75 bus system, Pattern-1)

Multilateral Transaction-1

Load bus	Losses corresponding to each load (MW)	Power transaction at each bus (MW)	Losses as % of the corresponding transaction	Transaction as % of total transaction	Loss allocated as % of total losses
20	4.2282	146.321			
25	14.2952	196.953			
27	11.9575	286.335			
37	3.2337	135.008			
42	-4.3843	935.715			
46	2.6166	146.272			
47	2.5688	69.759			
48	1.7367	47.563			
49	3.1136	80.211			
50	5.5979	189.112			
51	3.6813	54.048			
52	7.6671	91.955			
56	10.3172	131.265			
60	5.8931	69.432			
64	2.1145	53.140			
66	0.9847	29.700			
67	3.5474	90.233			
68	1.4882	40.115			
70	1.8988	21.840			
71	3.6708	85.835			
72	4.1718	49.145			
74	9.0060	269.492			
Total of multilateral-1	99.4048	3219.489	3.0876	58.8786	56.9982
Total of all the transactions	174.3982	5468.011	3.1895	100	–

Table3.11.2: Loss Allocation without FACTS Device Case-2 (a) [Chapter-2].

(UPSEB-75 bus system, Pattern-1)

Multilateral transaction-2

Load bus	Losses corresponding to each load (MW)	Power transaction at each bus (MW)	Losses as % of the corresponding transaction	Transaction as % of total transaction	Loss allocated as % of total losses
24	2.7665	187.085			
28	0.0247	102.046			
54	8.0826	136.062			
55	15.5610	229.604			
61	5.6342	89.290			
63	3.2765	49.322			
65	7.5603	123.306			
73	17.3713	399.682			
Total of multilateral-2	60.2771	1316.397	4.5789	24.0745	34.5626
Total of all the transactions	174.3982	5468.011	3.1895	100	-

Table 3.11.3: Loss Allocation without FACTS Device case-2 (a) [Chapter-2].

(UPSEB-75 bus system, Pattern-1)

Multilateral transaction-3

Load bus	Losses corresponding to each load (MW)	Power transaction at each bus (MW)	Losses as % of the corresponding transaction	Transaction as % of total transaction	Loss allocated as % of total losses
30	2.8495	173.766			
32	0.0943	59.900			
39	0.7726	65.276			
62	0.9267	76.825			
Total of multilateral-3	4.6431	375.767	1.2356	6.8721	2.6623
Total of all the transactions	174.3982	5468.011	3.1895	100	–

Table3.11.4: Loss Allocation without FACTS Device case-2 (a) [Chapter-2].

(UPSEB-75 bus system, Pattern-1)

Bilateral Transaction-1

Load bus	Losses corresponding to each load (MW)	Power transaction at each bus (MW)	Losses as % of the corresponding transaction	Transaction as % of total transaction	Loss allocated as % of total losses
34	0.0325	56.358	0.0577	1.0307	0.0186
Total of all the transactions	174.3982	5468.011	3.1895	100	-

Table3.11.5: Loss Allocation without FACTS Device Case-2 (a) [Chapter-2].

(UPSEB-75 bus system, Pattern-1)

Firm transaction

Load bus	Losses corresponding to each load (MW)	Power transaction at each bus (MW)	Losses as % of the corresponding transaction	Transaction as % of total transaction	Loss allocated as % of total losses
69	1.5793	56.0			
53	0.9641	82.0			
57	3.0554	150.0			
58	2.0607	94.0			
59	2.3812	118.0			
Total of firm transaction	10.0407	500.0	2.008	9.1441	5.7583
Total of all the transactions	174.3982	5468.011	3.1895	100	-

Table3.11.6: Summary of Loss Allocation without FACTS Device

Case-2 (a) [Chapter-2].

(UPSEB-75 bus system, Pattern-1)

Transaction	Power loss (MW)	Power transaction (MW)	Losses as % of the corresponding transaction	Transaction as % of total transaction	Loss allocated as % of total losses
Multl-1	99.4048	3219.489	3.0876	58.8786	56.9982
Multl-2	60.2771	1316.397	4.5789	24.0745	34.5626
Multl-3	4.6431	375.767	1.2356	6.8721	2.6623
Bilatl-1	0.0325	56.358	0.0577	1.0307	0.0186
Firm	10.0407	500.0	2.008	9.1441	5.7583
Total	174.3982	5468.011	3.1895	100	100

3.6 Conclusions

This chapter has presented an optimal power dispatch (OPD) model considering the FACTS devices in the system. The impact of two types of FACTS devices viz. TCSC and SVC on congestion management has been studied. In addition, a loss allocation strategy for bilateral and multilateral contracts has been suggested. From the results presented in this chapter, following main conclusions can be made –

1. Suitable placement of FACTS devices are helpful in increasing the loadability of the power system network, resulting in reduction of congestion in the transmission network and curtailment of desired power transactions.
2. The placement of TCSC, either in inductive mode, or in capacitive mode is not helpful in relieving the congestion of the power system network, when a line forming a part of radial feeder is overloaded. In this case, the loads at the end of the congested radial feeder should be reduced to bring the line flow of this line within the rated limit and then the placement of TCSC should be decided.
3. Loss allocation strategy suggested in this chapter is quite simple and non-iterative in nature.
4. There can be a negative loss allocation to some of the load (In UPSEB-75 bus system, losses allocated to load at bus-42 is negative). This indicates that the absence of that particular load may lead to the increment in the total transmission loss.

Chapter 4

Conclusions

In any deregulated power industry, where there are many buyers, the access to the transmission system by generators and customers should be managed in a non-discriminatory manner. In the deregulated market, it is possible that the trades between market participants can result in overloading of some of the electrical network components such as lines, transformers etc. The trading arrangements can be finalized analytically with the help of a transmission constrained optimal power dispatch solution. In such an optimal power dispatch formulation, the ISO may curtail the desired initial power transactions in a manner to bring the system within security limit. The present work made an attempt to present such an OPD formulation and to analyze various related problems. The main contributions of this thesis have been in

1. Proposing a modified optimal power dispatch model suitable for open access environment. The new set of power transactions was found as the closest point near the desired transactions within the security region.
2. Proposing a simple and non-iterative strategy for loss allocation, amongst various market participants, suitable for bilateral as well as multilateral transactions. The total power transmission losses were expressed using a general loss formula.
3. Assessing the role of two types of flexible AC transmission system (FACTS) devices, namely TCSC and SVC, on reducing the transmission congestion and curtailment of the contracted power.

The proposed models were tested on IEEE-14 bus system and UPSEB-75 bus Indian system. The main findings of the thesis are as following.

In chapter 2, a new optimal power dispatch model was presented. The transmission line flows have been considered as a linear function of the contracted powers using

generalized generation distribution factors The optimization problem has been solved by using the sequential quadratic programming method. The presence of multilateral, bilateral and firm contracts were considered. No curtailment in case of congestion was envisaged on the firm transaction The impact of premium price of willingness to pay to avoid curtailment by the transaction groups was studied. The main conclusions from the results presented in this chapter are as under-

1. Higher premium price of willingness to pay to a group lower the curtailment in the desired transaction of that particular group.
2. Higher premium price of willingness to pay simultaneously by two transactions benefits the bigger transaction group but hardly cause any benefit to the smaller power transaction group. This also causes severe curtailment to the remaining groups.
3. If any load, out of the multilateral transaction group, forms a separate bilateral group, this load suffers very badly but benefits the other bilateral/multilateral transaction groups even though the premium price of willingness to pay remains the same.
4. Congestion in a radially connected line may cause severe curtailment in the total power transaction.

In chapter 3, a simple and non-iterative strategy for loss allocation, amongst the various market participants was suggested. The total real power losses were expressed using a general loss formula. In this chapter, the role of two FACTS devices namely TCSC and SVC were studied on reducing the transmission congestion and curtailment of the contracted power. Static model of these devices had been considered. From the results presented in this chapter, the following conclusions are drawn.

1. Suitable placement of FACTS devices help in increasing the loadability of the power system network, resulting in reduction of congestion in the transmission system.
2. The placement of TCSC is not helpful in relieving the congestion of the power system network, when a line forming a part of radial feeder is overloaded. In this case the loads at the end of the congested radial line should be reduced to bring

the flow of this line within the rated limit and then the placement of TCSC should be decided.

3. Loss allocation strategy suggested in this chapter is quite simple, non-iterative in nature and quite general. It can be adopted to both bilateral and multilateral contracts.

As a result of the work presented in this thesis, following future scope of research are identified.

1. Chapter 2 had considered the constant reactive power load model. However, the impact of varying reactive power loads can also be studied.
2. Voltage dependent characteristics of the real and reactive loads can be included in the optimal power dispatch model.
3. In chapter 3, the losses were considered to be made good from one of the generator buses. A detailed model considering the procurement of losses from any bus by any trade and their allocation may be formulated
4. Impact of other FACTS devices such as STATCOM, TCPAR may be studied on the transmission congestion management.

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Appendix A

Data For IEEE-14 Bus Test System

(At 100 MVA Base)

The IEEE-14 bus system is shown in Fig A.1. The system data is taken from [40] and buses renumbered. The relevant data are provided in following tables.

Table A.1: Generator & Load data

a) Generator data

Gen. bus number	Voltage magnitude (p. u.)	Reactive power limit (MVAR)	
		max	min
1(slack)	1.08	40.0	0.0
2	1.08	60.0	0.0
3	1.08	100.0	-20.0
4	1.08	87.0	0.0
5	1.09	35.0	0.0

b) Load data

Load bus number	Reactive power demand(MVAR)	External shunt susceptance (p. u.)
6	31.6	0.0
7	54.9	0.0
8	0.0	0.0
9	16.8	-0.19
10	5.8	0.0
11	7.8	0.0
12	6.6	0.0
13	5.8	0.0
14	10.0	0.0

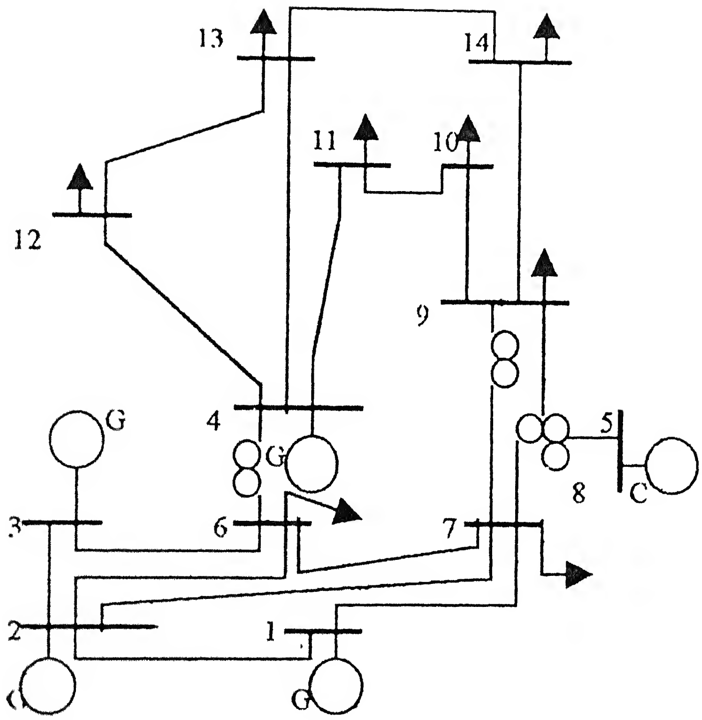

Fig A.1: IEEE-14 bus system
(buses renumbered)

Table A.2: Transformer Data

Line no.	From bus	To bus	Series impedance		Tap setting (p. u.)
			Resistance (p. u.)	Reactance (p. u.)	
1	4	6	0.000	0.25202	0.962
2	7	8	0.000	0.20912	0.978
3	7	9	0.000	0.55618	0.969

Table A.3: Line Data

Line no.	From bus	To bus	Series impedance		Shunt susceptance full line charging (p. u.)
			Resistance (p. u.)	Reactance (p. u.)	
4	1	2	0.0470	0.1980	0.0438
5	1	7	0.0670	0.1710	0.0346
6	2	3	0.0194	0.0592	0.0528
7	2	6	0.0569	0.1739	0.0340
8	2	7	0.0581	0.1763	0.0374
9	3	6	0.0540	0.2230	0.0492
10	4	11	0.0950	0.1989	0.0000
11	4	12	0.1229	0.2558	0.0000
12	4	13	0.0662	0.1303	0.0000
13	5	8	0.0000	0.1762	0.0000
14	6	7	0.0134	0.0421	0.0128
15	8	9	0.0000	0.1100	0.0000
16	9	10	0.0318	0.0845	0.0000
17	9	14	0.1271	0.2704	0.0000
18	10	11	0.0821	0.1921	0.0000
19	12	13	0.2209	0.1999	0.0000
20	13	14	0.1709	0.3480	0.0000

Appendix B

Data For UPSEB-75 Bus System
(At 100 MVA Base)

The UPSEB-75 bus system is shown in Fig. B.1. The system data is taken from [35] and buses are renumbered. The system double lines in parallel of same specifications have been considered as single line with equivalent impedance. The relevant data are provided in following tables.

Table B.1: Generator data

Bus number	Voltage-magnitude (p. u.)	Real power limit (MW)		Reactive power limit (MVAR)	
		Max.	Min.	Max.	Min.
1(slack)	1.03	900	100	400	-20
2	1.03	300	100	96	0
3	1.05	200	40	83	0
4	1.03	170	40	60	0
5	1.05	240	0	31	0
6	1.05	120	0	20	0
7	1.05	100	0	19	0
8	1.05	100	20	68	0
9	1.05	570	60	250	0
10	1.02	120	30	56	-35
11	1.02	200	40	105	0
12	1.05	1800	180	344	0
13	1.05	900	100	280	0
14	1.03	150	20	81	0
15	1.02	454	50	35	-70

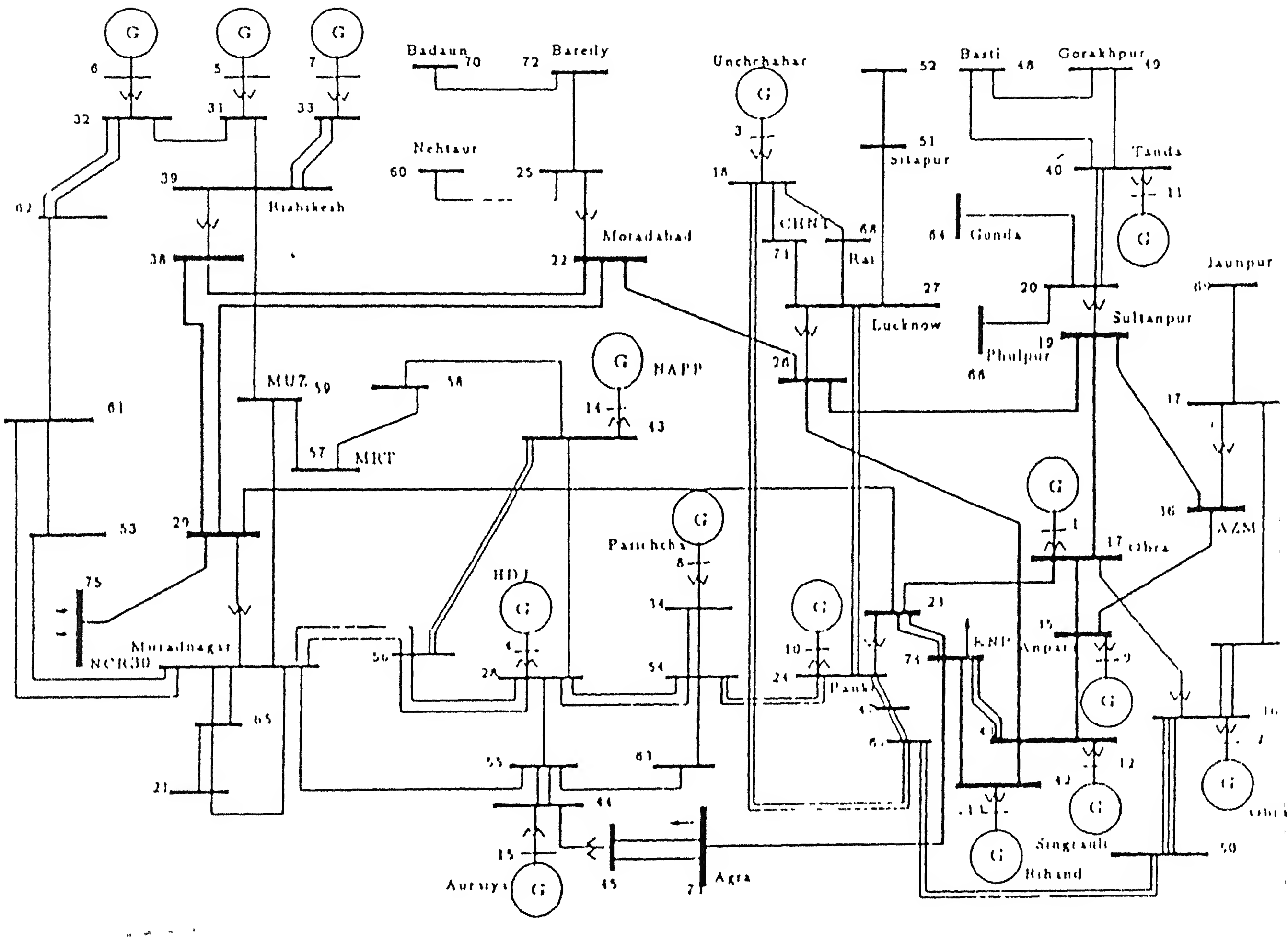

Figure B.1: 75-bus UPSEB system

Table B.2: Load bus data

Bus no.	Reactive load (MVAR)	Line reactor (MVAR)
16	27.56	-
17	0.0	100.0
18	0.0	-
19	0.0	50.0
20	33.93	-
21	0.0	-
22	0.0	50.0
23	0.0	100.0
24	40.53	-
25	43.43	-
26	0.0	163.0
27	40.7	-
28	28.35	-
29	0.0	100.0
30	44.24	-
31	0.0	-
32	11.59	-
33	0.0	-
34	83.84	-
35	0.0	50.0
36	0.0	50.0
37	40.93	-
38	0.0	-
39	29.46	-
40	0.0	-

Table B.2 Cont.....

41	0.0	223 0
42	0.0	63.0
43	0.0	-
44	0.0	-
45	0.0	-
46	83.36	-
47	8.77	-
48	13.97	-
49	51.58	-
50	74.94	-
51	0.62	-
52	-18.15	-
53	-0.33	-
54	29.0	-
55	31.08	-
56	34.32	-
57	18.53	-
58	11.29	-
59	11.01	-
60	7.42	-
61	6.58	-
62	18.13	-
63	5.31	-
64	13.33	-
65	12.81	-
66	15.18	-
67	10.55	-
68	33.60	-
69	32.53	-
70	2.30	-
71	21.36	-
72	11.76	-
73	0.0	50.0
74	0.0	283.0
75	0.0	-

Table B.3: Transformer Data

Line no.	From bus	To bus	Series impedance		Tap setting (p. u.)
			Resistance (p. u.)	Reactance (p. u.)	
1	19	20	0.00065	0.02604	1.0
2	17	16	0.00065	0.02604	1.0
3	22	25	0.00065	0.02604	1.0
4	23	24	0.00065	0.02604	1.0
5	26	27	0.00065	0.02604	1.0
6	29	30	0.00043	0.01736	1.0
7	36	37	0.00065	0.02604	1.0
8	38	39	0.00130	0.05208	1.0
9	45	44	0.00056	0.02222	1.0
10	16	2	0.00123	0.02469	1.0
11	18	3	0.00000	0.02917	1.0
12	17	1	0.00073	0.01460	1.0
13	28	4	0.00306	0.06135	1.0
14	31	5	0.00235	0.04710	1.0
15	32	6	0.00514	0.10285	1.0
16	33	7	0.00549	0.10978	1.0
17	34	8	0.00000	0.04860	1.0
18	35	9	0.00049	0.01943	1.0
19	24	10	0.00243	0.04860	1.0
20	40	11	0.00770	0.02720	1.0
21	41	12	0.00016	0.00591	1.0
22	42	13	0.00030	0.01199	1.0
23	43	14	0.00000	0.02841	1.0
24	44	15	0.00000	0.02273	1.0

Table B.4: Line Data

Line no.	From bus	To bus	Series impedance		p. u. shunt susceptance (Half line charging)
			Resistance (p. u.)	Reactance (p. u.)	
25	16	46	0.00810	0.03880	0.14030
26	16	50	0.00993	0.04746	0.38643
27	17	19	0.00468	0.04777	0.52450
28	17	23	0.00785	0.07990	1.04738
29	23	29	0.00806	0.08169	1.06808
30	20	64	0.01830	0.09270	0.07390
31	19	26	0.00294	0.02997	0.39206
32	47	50	0.01093	0.05221	0.18892
33	47	67	0.00662	0.03164	0.11451
34	24	27	0.00505	0.02416	0.08730
35	24	54	0.02910	0.06171	0.22327
36	27	51	0.01600	0.08100	0.64400
37	51	52	0.01550	0.09400	0.06300
38	25	60	0.01660	0.08430	0.06720
39	25	43	0.01270	0.06410	0.05220
40	34	54	0.01770	0.08510	0.30260
41	54	28	0.01060	0.05060	0.18320
42	28	43	0.00580	0.02900	0.02370
43	28	56	0.00370	0.01780	0.06440
44	56	30	0.00490	0.02370	0.85900
45	30	57	0.00750	0.03840	0.03110
46	53	30	0.00679	0.03412	0.02782
47	53	61	0.00666	0.03390	0.02672
48	30	61	0.01440	0.07310	0.05850
49	57	58	0.00670	0.03390	0.02670
50	57	59	0.00583	0.07310	0.02346
51	59	39	0.01410	0.03390	0.05700
52	39	32	0.01440	0.02956	0.05900
53	39	33	0.00705	0.07180	0.11400
54	54	63	0.00990	0.07250	0.04010
55	55	63	0.00780	0.03570	0.03140
56	61	62	0.01160	0.03090	0.04750
57	62	32	0.00690	0.03980	0.11280

Table B 4 Cont.....

58	31	32	0.00030	0.05830	0.00805
59	35	36	0.00479	0.03500	0.63614
60	46	37	0.01732	0.00253	0.06973
61	19	36	0.00254	0.04880	0.33798
62	17	35	0.00051	0.08780	0.06760
63	20	40	0.00380	0.02584	0.09420
64	40	48	0.00830	0.00517	0.03340
65	74	41	0.00927	0.05940	1.23293
66	74	41	0.00833	0.08478	1.10853
67	74	73	0.00559	0.05686	0.74354
68	26	22	0.00650	0.06617	0.86521
69	29	22	0.00260	0.02646	0.34610
70	26	41	0.00823	0.08375	1.09503
71	48	49	0.00930	0.04750	0.03740
72	49	40	0.01330	0.06680	0.05420
73	38	29	0.00370	0.03762	0.48870
74	38	22	0.00325	0.03307	0.43264
75	18	47	0.00437	0.02552	0.09399
76	30	65	0.00248	0.01156	0.04294
77	41	42	0.00031	0.00310	0.04056
78	42	74	0.00918	0.09306	1.21650
79	20	66	0.01325	0.06667	0.05416
80	23	74	0.00013	0.00155	0.02704
81	24	67	0.00124	0.00593	0.02107
82	18	68	0.00336	0.01963	0.01808
83	18	71	0.01344	0.07852	0.07230
84	27	68	0.01344	0.07852	0.07230
85	27	71	0.00336	0.07963	0.01808
86	25	72	0.01598	0.08108	0.06436
87	43	58	0.01315	0.06696	0.05278
88	43	56	0.00499	0.02397	0.08523
89	55	44	0.00998	0.04794	0.17046
90	73	45	0.00121	0.01109	0.72815
91	29	75	0.00051	0.00517	0.06760
92	37	69	0.01212	0.06100	0.04956
93	70	72	0.00878	0.04430	0.03580
94	21	65	0.00083	0.00396	0.01431
95	21	30	0.00695	0.03500	0.02843

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This book is to be returned on the date last stamped.
